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Soil moisture dynamics in forest monocultures of beech, larch and spruce in a drought-prone region of Central Bohemia

Doctoral Dissertation

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Declaration

I hereby declare that I have written this doctoral thesis entitled **"Soil Moisture Dynamics in Forest Monocultures of Beech, Larch and Spruce in a Drought-Prone Region of Central Bohemia"** independently and that I have properly cited all sources of information, in accordance with the methodological guidelines on ethical principles for writing academic theses.

Prague July 31, 2026 Ing. Marta Kuželková

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Abstract

Forests provide wide range of ecosystem services, including water retention, erosion control and microclimate regulation. Tree species differ in functional traits that may influence forest hydrology. Under ongoing climate change, increasing evapotranspiration demand and more frequent weather extremes may alter the balance between soil water recharge and depletion, putting the forest vitality at risk. Robust field data are therefore needed to better understand how contrasting tree species affect soil water dynamics under drought-prone conditions.

This dissertation compares soil moisture dynamics under three ecologically contrasting and regionally important tree species: Norway spruce, European beech, and European larch. A long-term soil moisture monitoring network was established and evaluated over the 2021–2026 monitoring period and complemented by soil water potential measurements. The results showed pronounced and statistically significant differences in surface soil moisture among studied tree species. In surface soil layers, spruce repeatedly showed an early water depletion already in February. In contrast, beech and larch stands generally remained in a recharge phase until rapid depletion starting in mid April to early May, reaching even to deeper soil layers. Consequently, during peak summer, soil water storage in beech and larch stands dropped under spruce levels. However, during the winter recharge period, soil water storage under beech and larch was restored to saturation, whereas spruce often entered the following growing season with a water deficit (-10 kPa). However, the exceptionally warm year 2024 disrupted typical spring pattern. Under larch, soil moisture depletion occurred shortly after spruce, suggesting that warming may modify the usual species-specific differences in soil water dynamics. At the end of 2024 the soil water deficit approximated by soil potential decreased to -100 kPa in spruce even though a extreme precipitation occurred in September, recharging the beech and larch soil.

The observed differences are likely associated with species-specific functional traits. Evergreen spruce appears to be disadvantaged by year-round interception, prolonged transpiration demand, and reduced recharge ability related to the character of its organic soil layer and lateral root system. In contrast, the seasonal loss of foliage and deeper rooting system of beech and larch trees allow more effective soil water recharge. These findings demonstrate that tree species composition can substantially affect soil water regimes under drought-prone conditions and may support forest adaptation strategies in Central European forests.

Contents

Preface

As a child, I used to spend a lot of time in nature. At first while attending a summer family camp and later when joining the local canoeing kids club. My connection with nature and water was shaped naturally during that time, as I learned to navigate a boat through the gentle rapids of Bohemian rivers and camp under the open sky by a bonfire.

Thirteen years later, when I had to decide whether to go to university after graduation, I made what turned out to be a lucky guess and enrolled in the Landscaping bachelor's programme in my hometown of Prague. After overcoming a few initial struggles, I successfully completed my bachelor's degree and, largely driven by persistence in the chosen path, continued on to finish my Master's as well. However, during that time, my motivation gradually changed. Instead of simply fulfilling the requirements for a degree, I discovered the joy of understanding how things fit together and of building knowledge that reveals the complexity of natural processes. At that point, I decided to pursue an academic path. Six years later, I am ready to share the knowledge I have gained through my research.

Allow me to take you through the findings I discovered during my Ph.D. studies at Czech University of Life Sciences Prague. Join me on this path and read the story of precipitation water that is partitioned by the tree canopies, intercepted or concentrated by their structures and channelled down to soak into the soil, replenishing one of the vastest water reservoirs on earth.

1

Introduction

1.1 A contextual overview

Forests represent an essential terrestrial ecosystems. Their importance has traditionally been associated primarily with timber production. However, forests provide a much broader range of ecosystem services, including carbon sequestration (Canadell & Raupach, 2008), biodiversity enrichment, and microclimate regulation (Costanza et al., 1997). From a hydrological perspective, healthy forest ecosystems contribute to water retention, reduction of surface runoff, erosion control, and improved infiltration capacity (Borrelli et al., 2017; Gyssels et al., 2005). Trees and forest soils influence the redistribution of precipitation, thereby affect the replenishment of soil water resources (Bargués Tobella et al., 2014; Gonzalez-Sosa et al., 2010). This is particularly important because soil represents a key water reservoir that transforms irregular precipitation inputs into a more continuous supply of water for vegetation, groundwater recharge, and streamflow (Hillel, 1998; Kutílek & Nielsen, 1994).

The cooling effect of vegetation has been widely recognised and studied, particularly in urban environments (Moss et al., 2019), where its benefits are often linked to the reduction of heat stress and air-conditioning demand. In contrast, the role of forests in regulating local climate and energy fluxes in open landscapes has received comparatively less attention (Sun et al., 2017). However, under globally rising temperatures, the role of forests in local and regional climate regulation becomes increasingly relevant (Ellison et al., 2017). In this regard, forests should be understood not only as passive responders to climatic conditions, but also as active components influencing water and energy fluxes within the landscape.

The hydrological balance of forest stands is strongly affected by tree species composition. Different tree species exhibit contrasting ecohydrological traits that may substantially alter the water cycle within forest stands (Carlyle-Moses & Schooling, 2015). Species-specific characteristics such as canopy structure, phenology, rooting architecture, litter quality, and their effects on soil properties may influence precipitation partitioning, infiltration pathways, soil water storage, and water availability (Van Stan et al., 2020). As a result, forest stands composed of different tree species may differ not only in productivity and ecological stability, but also in the management of water.

In Central Europe, the natural tree species composition has been substantially altered by historical forest management. From the early nineteenth century, Norway spruce (*Picea abies*) monocultures were widely established because of their favourable timber properties, rapid growth, and high economic value (Nožička, 1957). Although spruce naturally occurs mainly in colder and wetter mountain environments, it was extensively planted outside its native ecological optimum, including lower and drier regions. Here, since higher temperatures, the benefit in the form of increased growth was achieved. This management strategy was economically rational under past climatic conditions, but it has become increasingly problematic under current and projected climate. In Central Europe, drought stress has been repeatedly linked to increased susceptibility of Norway spruce to bark beetle outbreaks, which have caused extensive forest decline in recent decades (Hlásny, Zimová, et al., 2021). However, drought related mortality has also been observed in other tree species (Obladen et al., 2021).

The climatic conditions under which many present-day forests were established are now changing. Increasing air temperature promotes atmospheric evaporative demand, prolongs the vegetation season, and increases the risk of drought stress in forest ecosystems. Europe has been identified as one of the fastest warming regions globally (2.3°C since the pre industrial age), accounting for almost twice of the global increase (1.2°C) (WMO, 2023). This raises concerns regarding the vitality of forest stands established under past climatic assumptions, especially those dominated by species currently growing outside their optimal ecological range. For example, Čermák et al. (2021) estimated that while during the period 1961–1990 about 46.0% of the Czechia provided optimal conditions for spruce growth, only 11.3% is expected to remain suitable by 2041–2060.

Trees are long-lived organisms with slow generational turnover, therefore their capacity for rapid adaptation to changing environmental conditions is limited (Köhl et al., 2010). Consequently, forest composition established under historical economic and climatic assumptions may no longer represent an optimal solution for future environmental conditions. Although timber production remains an important societal need, ongoing climate change may increasingly affect forest productivity itself through declining vitality, drought stress, and tree mortality (C. D. Allen et al., 2010). Since it takes over a century to grow a harvest-ready forest, present-day decisions regarding tree species composition will influence ecosystem functioning for many future decades.

Although the transition towards more resilient forest ecosystems in Czechia is already underway (Ministry of Agriculture of the Czech Republic, 2025), a large proportion of current forests were established decades ago and still reflects past climatic and economic conditions. This raises concerns regarding the future vitality of these forests. Given the close connection between forest and the hydrological cycle, large-scale forest decline may have consequences not only

for timber production, but also for water retention, soil moisture availability, overheating and landscape drought resilience.

Previous research has established that tree species can influence forest hydrology and consequently the stand-level water balance. However, it remains unclear how these relationships are expressed under changing climatic conditions. Increasing evapotranspiration demand, prolonged growing seasons, and more frequent extreme precipitation and drought events may alter the balance between soil water recharge and depletion. Therefore, a better understanding of hydrologically relevant forest responses is needed to assess the capacity of forest stands to maintain vitality under drought-prone conditions.

Soil water provides an integrative indicator of these complex ecohydrological responses, as it reflects the combined effects of precipitation input, infiltration, soil water redistribution, root water uptake, and evapotranspiration losses. Although monocultures are generally not considered a model of climate-resilient forestry, they reflect the current state of forests in Central Europe and provide a convenient setting for comparing species-specific effects under similar site conditions and meteorological forcing. This dissertation leverages this opportunity by focusing on soil moisture dynamic in monocultures of European beech, European larch, and Norway spruce in a drought-prone region of Central Bohemia.

1.2 Aims and focus

The main aim of this thesis is to comprehensively describe and compare the dynamics and patterns of soil moisture in forest monocultures composed of three dominant and ecologically contrasting tree species: European beech (*Fagus sylvatica*), European larch (*Larix decidua*), and Norway spruce (*Picea abies*). The study focuses on drought-prone conditions, where species-specific differences in soil water availability, recharge, and depletion may become particularly important. A further aim is to provide a process-based interpretation of the observed patterns and to discuss their implications for future climate-resilient forest management.

Based on the aforementioned context, several research questions were formulated to guide the research:

- How do soil moisture regimes differ among forest monocultures of the selected tree species under drought-prone conditions?
- How do these patterns vary seasonally, across years and with soil depth?
- What is the total soil water storage across soil profiles?
- How can the observed soil moisture patterns be interpreted in relation to known species-specific ecohydrological traits and processes?

As an evergreen tree, the spruce is expected to show a more stable response to environmental inputs throughout the year, as it is less affected by phenological changes, particularly in foliage, than the deciduous beech and larch. The deciduous character of these species is anticipated to have a significant effect on the forest water balance, resulting in different responses during the leaf-off and leaf-on periods. Given the differences among the selected tree species in crown architecture, root systems, and water requirements, their species specific traits are further expected to modify the soil water relationship and produce distinct patterns of soil moisture.

To address the research questions, a long-term continuous monitoring network of soil moisture was established. For this purpose, a microclimatic stations TMS were used (Wild et al., 2019). The dataset collected between 2021 and 2026 at 15-minute intervals produced more than 12 million observations across the studied tree species and represent the core dataset of this thesis. These measurements were complemented by independent observations of soil water potential and by a detailed characterisation of the vegetation and soil of the monitored forest environments. Although the study was conducted at a local scale in a drought-prone region of Central Bohemia, the findings may contribute to a broader understanding of vegetation-mediated hydrological processes under changing climatic conditions.

1.3 Structure of thesis and contribution

The dissertation is structured as a monograph. Part of the presented results is based on the published journal article "Tree trait-mediated differences in soil moisture regimes: a comparative study of beech, spruce, and larch in a drought-prone area of Central Europe" (Kuželková et al., 2024), which focused on seasonal differences in shallow soil layers (0–15 cm and 15–30 cm) in the period from mid 2021 to 2022. A substantial part of the thesis further expands these findings using additional years of monitoring, analysis of deeper soil layers reaching to depths of 115 cm and soil water potential measurements. These extended results are currently being finalised for submission in a follow up journal article.

In addition to the analytical results, an important contribution of this thesis lies in the establishment, testing, calibration, and long-term maintenance of the soil monitoring network. Although such technical and methodological work is not always fully visible in the final scientific outputs, it formed a necessary foundation of the presented results. Prior to field installation, each TMS station was individually tested under laboratory conditions. In this process, noticeable variability in the early emissions of the TMS station was detected and discussed with the manufacturer. These insights led to improvements in the manufacturing process and produced an increase in the accuracy of soil moisture measurements. Moreover, since the limited calibration specifications

provided by the manufacturer were focused on non organic soils, soil-specific calibrations were developed to reflect the forest environment. The calibration methods included a laboratory based soil measurements and further refined field methodology. These advances were documented in an electronic calibration handbook for TMS stations (Jačka et al., 2023).

In the following Chapter (2), the current state of knowledge through a literature review is provided. Chapter 3 is dedicated to a detailed description of the research site, starting with the general climatic and geomorphological characteristics and further describing the vegetation and soil conditions. Following Chapter 4 summarizes the methods and datasets used for data analyses. Chapter 5 presents the obtained results, which are further discussed together with the context, literature, and limitations in Chapter 6. Finally, the thesis is concluded in last chapter.

2

Literature review

2.1 Forests in a changing climate

Forests perform an active role in the climate system and contribute significantly to climate change mitigation. As major carbon sinks, they reduce atmospheric greenhouse gas concentrations by sequestering carbon in biomass and soils. Although forests can also act as carbon sources, their global net balance remains negative, indicating that they capture substantially more carbon than they emit (Pan et al., 2011). Beyond carbon sequestration, forests provide several hydrologically relevant ecosystem functions, including water retention, microclimate regulation, soil protection, and erosion control. Vegetation affects the surface energy balance and can reduce landscape temperature, particularly during warm periods (Hesslerová et al., 2013). Forest canopies are able to buffer temperature extremes by creating a local microclimate. This effect is not limited to summer cooling, as forest act as a thermal insulator and remain warmer during cold periods when compared to open landscape (De Frenne et al., 2019).

However, the relationship between forests and water availability is more complex and scale-dependent. In order to sustain its proper functions, the forest has a significant water requirements. On a local scale, due to high evapotranspiration forested land may reduce water availability. This is mainly supported by the studies focused in runoff. For example, Farley et al. (2005) reported that on average the afforestation of grasslands, reduces the annual run-off by 44%. However, Ellison et al. (2012) objects, that at the same time, in the larger scale, forest contribute to increase in precipitation. Furthermore the forests have a great ability to retain water, promote the recharge of soil reservoir and protect soil from erosion (Bruijnzeel, 2004).

These effects, however, are also affected by broader context, such as tree age, strand structure and species composition. In a review article on forest restoration Jones et al. (2022) reported that while both old-growth forest and forest plantation have a relatively high evapotranspiration, they differ in the infiltration ability. This is reflected in the deep soil moisture under the root zone and lead to consistent water yield in old-growth and low water yield from managed forest plantations Jones et al. (2022).

Changing climate has substantial effect on the conditions for tree species

distribution. In the future, a decreased variety of occurrence range is expected for native tree species (Wessely et al., 2024). This has the potential to alter the structure of large portion of European land. Climate change is repeatedly marked as a significant challenge for current forestry and has been repeatedly linked with increased tree mortality (Hartmann et al., 2022). In order to sustain the functions of forest, it is necessary to seek for adaptations that will form the future climate-resilient forests.

2.1.1 Changing climate, drought and water availability

Climate change is associated with rising temperatures and the intensification of hydrological extremes. Higher temperatures increase atmospheric evaporative demand and thereby raise vegetation water requirements. Since the rate of warming in Europe exceeds the global average, substantial changes in the water balance can be expected. Although total annual precipitation is likely to remain comparable, its seasonal distribution is expected to change. Subsequently, longer periods without precipitation followed by heavy rainfall are therefore likely to become increasingly common (IPCC, 2023).

These changes affect drought development and its propagation through the soil–plant–atmosphere continuum. Drought starts as a meteorological anomaly, however can further propagate into soil moisture (agricultural drought) and subsequently put vegetation under water stress (W. Wang et al., 2016). However, this transition is not immediate and depends on antecedent soil moisture conditions, soil properties, rooting depth and vegetation water demand (A. Gupta & Karthikeyan, 2024). A sufficient soil water storage can delay and dampen the drought propagation. Therefore, soil moisture drought usually follows meteorological drought with a time lag, while shallow soil layers tend to respond more rapidly than deeper layers (Zhou et al., 2025). A prolongation of soil moisture drought results in hydrological drought, affecting the surface and subsurface water. This results in decreased levels in rivers, streams and reservoirs (Van Loon, 2015).

Drought development may also be further intensified by compound events, when precipitation deficits coincide with high temperatures. In Central Europe, such compound droughts are becoming more frequent during the summer seasons (Markonis et al., 2021).

Soil represents a reservoir for water that buffers the discontinuous input of precipitation and transforms it into a continuous water supply for vegetation (Hillel, 1998; Kutílek & Nielsen, 1994). Therefore it is important for overcoming a period of drought. An efficient recharge of soil is essential for replenishing water reserves. However, after a prolonged period of drought, the dry soil may temporarily became hydrophobic and decrease the infiltration ability (Doerr & Thomas, 2000). Since the expected uneven distribution of precipitation, this is likely to frequently occur.

Once soil water storage declines below levels that can sustain transpiration,

soil water availability becomes a limiting factor for stomatal conductance (Drake et al., 2017), carbon assimilation and tree growth (Timofeeva et al., 2017).

2.1.2 Drought in forests

Under reduced soil water availability, forests may gradually lose vitality, reduce their physiological functioning and under severe or prolonged stress, experience increased tree mortality. McDowell et al. (2008) proposed a hydraulic based framework linking drought-induced tree mortality with carbon balance and resistance to biotic agents. The tree mortality may result from several interacting mechanisms rather than from a single isolated cause. One such pathway is hydraulic failure that occures with declining soil water availability and together with high atmospheric evaporative demand, increases the tension in xylem to the point where air bubbles enter the system. This process is referred to as cavitation, whereas the resulting air blockage of xylem conduits is referred as embolism (Carluccio et al., 2023). The air blockage decreases the xylem conductivity and subsequently the tree is no longer able to sustain its physiological functions.

A second pathway is related to stomatal regulation. Stomatal closure reduces transpiration and can therefore protect the plant hydraulic system from excessive water loss and cavitation. However, closed stomata also restrict carbon uptake and photosynthesis. Under prolonged drought, the tree increasingly rely on its stored carbohydrates to maintain its functions, as the supply is restricted. If drought persists, this imbalance between carbon demand and carbon supply may contribute to carbon starvation (McDowell et al., 2008).

Under drought stress, the tree is weakened and become prone to biotic agents such as insects and fungi. In healthy condition, the trees have their mechanisms to cope with such infestations, however under drought stress the defence ability is progressively weakened (Jactel et al., 2012). Biotic agents should be understood as interacting with hydraulic and carbon-related stress rather than as a fully independent mechanism (McDowell et al., 2008). One of such main pathogens is bark beetle (*Ips typographus*). While drought and warm conditions, may be challenging for trees, for insect represent a favourable conditions as they provide a longer period for population growth and reduce the winter mortality (Robbins et al., 2022). In central Europe, recent dry years have been closely linked to the escalation of bark beetle outbreaks. In particular, the extreme 2018 drought was followed by a unprecedented mortality of spruce forests (Pirtskhalava-Karpova et al., 2024).

Xylem character further affect the hydraulic drought response of trees. Gymnosperms (mostly coniferous trees) are evolutionary older and have their conductive tissues formed by tracheids a thin elongated cells with thickened lignin walls. Angiosperms (mostly broadleaved trees), conduct water via vessels, that are wider and have a thinner cell wall. In general, wider vessels allow higher hydraulic conductivity and potentially higher transpiration rates, whereas

the tracheid-based xylem of conifers is commonly associated with slower but hydraulically safer water transport, resistant to embolism (Sperry et al., 2006).

Due to differences in structural, physiological and ecological traits, tree species differ in their characteristic drought response strategies. McDowell et al. (2008) describes the characteristics of isohydric and anisohydric patterns of hydraulic regulation during drought. Species with isohydric regulation tend to close their stomata earlier, thereby reducing further water loss, but at the cost of restricted carbon uptake and photosynthesis. In contrast, species with anisohydric regulation maintain stomatal conductance and transpiration for longer as soil water availability declines, but this may increase the risk of xylem embolism and hydraulic failure. Rather than representing two discrete categories, later studies view this behaviour as a continuum of stomatal and hydraulic regulation strategies ranging from isohydric to anisohydric behaviour (Klein, 2014).

However, these regulatory patterns may vary with local environmental conditions. Soil water availability, topographic position, access to subsurface water and atmospheric evaporative demand can alter plant water dynamics and thereby affect the apparent behaviour of a given species (Feng et al., 2019).

Tree mortality represents the ultimate consequence of drought damage, but more subtle signs of water stress can be observed before trees die. Among the early visible symptoms are crown desiccation, premature leaf or needle discolouration, premature leaf senescence and early leaf shedding (Češljar et al., 2025). Drought stress can also reduce tree growth and development, including lower radial and shoot growth, reduced sapwood production and the formation of smaller foliage in the following growing season (Bréda et al., 2006; Camarero et al., 2015). The drought also affect the bellow ground biomass, under water-limited conditions, trees may adjust carbon allocation towards belowground structures involved in water uptake. This can result in a higher root-to-shoot ratio, partly because aboveground growth is often reduced more strongly than root growth. Tree species adapted to drier conditions generally tend to develop deeper root systems and allocate relatively more biomass belowground. However, under severe or prolonged drought, fine-root biomass may also decline, which can limit further water uptake and post-drought recovery (Brunner et al., 2015).

In addition to drought, trees may also be exposed to heat stress, potentially causing a permanent damage to plant tissues. When combined with soil drought, the vegetation is unable to cool its surface through evaporative cooling during transpiration. As a result, the negative effects of high temperature and water limitation multiply. The extent of heat and drought induced damage, including mortality, depends on the severity, duration and timing of the stress event, as well as on soil water availability and species-specific tolerance (Teskey et al., 2015).

2.1.3 European forests

About one third of Europe is covered by forest. However, the distribution of forested area across the continent is uneven and highly heterogenous. The vegetation ranges form a vast boreal forest in Scandinavia, temperate mixed forest in the central regions, and the drought-adapted sparse vegetation of Mediterranean. Therefore the forest in Europe is diverse in its structure, species composition and age. While the highest proportion of forested land is in Northern Europe, in Central Europe this is on average 28%. Overall, the forested area is slowly expanding. Since the 1990 it increased by 11%. However, the rate of growth is decreasing in the last decade (Forest Europe, 2026).

In Europe a vast majority of forests has been altered by human activities in past. Only a fragments of primary forest remain in the south and central Europe, perhaps with the exception of Romania. The remaining primary forests are concentrated predominantly in the Northern Europe, spanning over Finland, Norway and Russia (Sabatini et al., 2021). Most of those forests were protected by its remote location or harsh environment.

Most of the countries in Europe account for about 30-45% of forested land, while significantly larger proportion is located in Baltic region, Austria, Slovenia and Montenegro (Fig. 2.1). On the other hand, the lowest proportion of forests is in Ireland, the United Kingdom, and Iceland (Forest Europe, 2026). Coniferous forests consisting of 43%, are predominantly located in Northern Europe. Approximately the same proportion (40%) consists of broadleaved forest and the remaining 17% consists of mixed forests.

Currently, more than 70% of European forests consists of more than one tree species, however most of it consists of two-species composition. While in some areas a mixed species composition may help to establish a resilient forest, it is not a rule, as some forest, for example boreal forest are naturally dominated by single species (Forest Europe, 2026).

European forest are in transition phase as the previously homogenized and simplified forest structure is being converted to more diverse tree species composition, as it provides benefits for forest resilience upon disturbances and also increases its ecological value. This is slowly being reflected in European tree species composition. In general, the diversity in forest contribute to an increase in resilience towards abiotic disturbances, in the case of biotic factors, this is more context dependant. While diversity helps with insect outbreaks, it may promote the impact of generalist herbivores, seeking for variability (Pretzsch et al., 2017).

Majority of European forests consists of Europe native species composition, with a limited proportion of introduced species. However, changing climate reduces the options of native and also climate-adapted tree species, suitable to grow in future climatic conditions (Wessely et al., 2024). In future, an introduction of non native trees might be one possible management option, in order to sustain the vitality of European forests. However, a careful consideration on

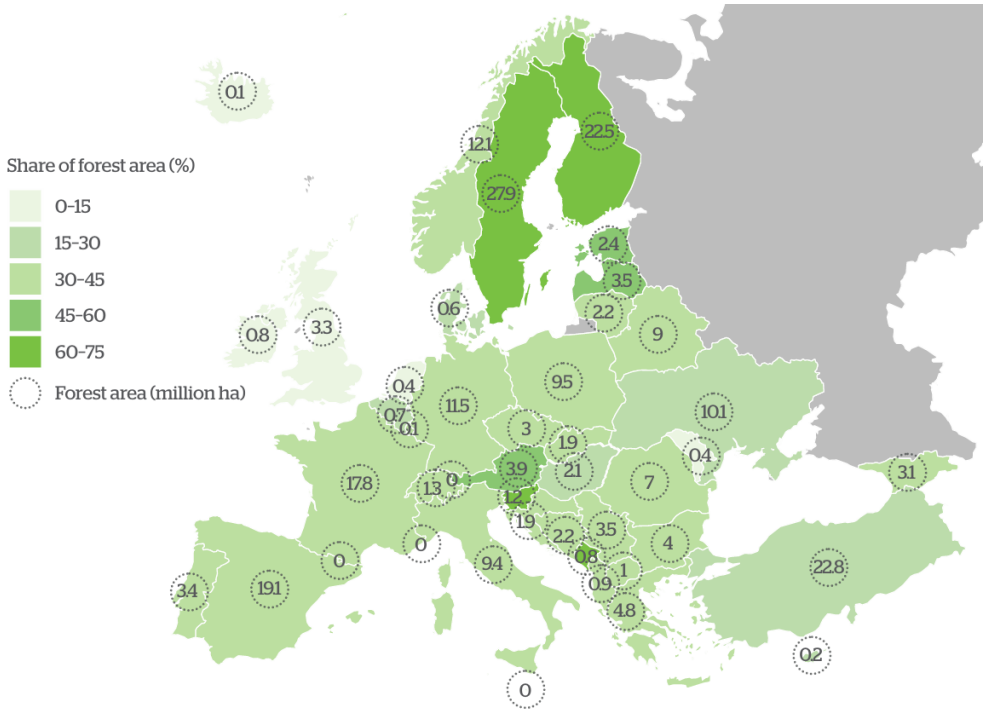


Figure 2.1: The proportion of forest for individual countries of Europe. Most countries are within a range of 30 – 45 % of forested land. Adapted from State of Europe's Forests 2025 report.

the ecosystem needs to be taken into account (Pötzelsberger et al., 2020).

European forests are important producers of roundwood, a key material for construction, furniture, paper, and other components. Particularly significant is the production in the Northern and Central Europe. Among the countries with high production volume are Germany, Sweden and Finland. Although Czech republic is at 7th place, all of the above countries are significantly larger in area (Forest Europe, 2026).

In the last decades, wood production has been intensified. An abrupt increase in harvested forest area was observed across Europe for the period of 2016–2018 relative to 2011–2015. This accounted for 49% increase in some regions. While the most pronounced changes were detected in northern Europe, for the Czech Republic, this accounted for 25% (Ceccherini et al., 2020).

Despite the intensification of wood production, the total wood stocks are increasing. However, significantly different conditions are observed across Europe. While some parts are being afforested, in Central Europe the combination of regular harvest and salvage logging after significant disturbances in recent years, resulted in decrease of total net annual increment (Forest Europe, 2026).

Since 1970, the post damage salvage logging were mostly connected to wind (46%), followed by forest fire (24%) and bark beetle (17%). However, in the last 20 year the bark beetle outbreaks significantly increased and nearly doubled its contribution on annual wood harvest (Patacca et al., 2023). Reduced vitality and increased mortality was observed in the past decades. In general, drought was identified as a preceding factor, reducing the forest resilience towards further damage. This was reported for bark beetle and fire (Senf et al., 2020).

Central European forests have been strongly affected by recent climate change related drought and heat events, particularly through reduced vitality, increased tree mortality, and large-scale bark beetle disturbances (Hlásny, König, et al., 2021). In the period 2018 - 2022 Central Europe showed the highest vulnerability, impacting both coniferous and deciduous trees (Knutzen et al., 2025). Considering also its relatively tight connection to wood production, the need for forest adaptation is highly relevant.

2.1.4 Forests in Czech Republic

In the Czech republic, 35% of land is evidenced as forested land. The majority (more than 70%) of these forests are managed primarily for production. Although the proportion of production-oriented forests has been slowly decreasing over the last 40 years (Ministry of Agriculture of the Czech Republic, 2025), still, it makes an important industrial sector. This reflects the current state of forests in Czechia.

Currently, approximately 67% are coniferous forests, represented by spruce (45%) and pine (16%). Minor representation has larch (4%) and under 2% fir. The broadleaves consists of 30%, while the remaining 3% of the area consists of cleared sites to be reforested in following years. The main broadleaved tree

species are represented by 10% of beech, 8% percent of oak and 3% of birch (Ministry of Agriculture of the Czech Republic, 2025).

The proportion of coniferous species grows with the altitude. While in lowland (under 400 m) coniferous trees consists of 31.6%, in the middle altitudes (400 - 700 m) they already consist a dominant 59.1% (Ministry of Agriculture of the Czech Republic, 2025). However, these altitudes are according the forest vegetation zones still typical for broadleaved forests (Dujka et al., 2023). Above the elevation of 700 m, the percentage of coniferous trees is 76.1% (Ministry of Agriculture of the Czech Republic, 2025).

In recent years, forest management has increasingly focused on improving forest resilience through changes in stand structure and tree species composition. This transition includes a gradual increase in the proportion of broadleaved tree species. A targeted recommanded tree species composition is spruce 28 %, beech 22.5%, pine 13.2%, oak 12.8%, birch 7.6% and larch 4.2%. Therefore, on the expense of spruce and pine trees, more beech, oak and birch trees are to be planted (Ministry of Agriculture of the Czech Republic, 2025). This is expected to increase the resilience and stability of future forest under climate change.

However, the shift in forest composition raises economical concerns for Czech forestry. The traditional forest management has long been strongly linked to Norway spruce, which was favoured for its easy regeneration, simple management and profitability. Therefore, the expected decline in coniferous timber supply and increasing share of broadleaved species may reduce timber revenues unless the wood processing sector adapts to use of broadleaved timber (Šebek et al., 2024).

The present dominance of coniferous stands in Czech forests is rooted in the historical transformation of forest management. From the 18th century, increasing demand for wood, driven by mining, metallurgy, and the glass industry, led to intensive exploitation and degradation of many forest areas (Lenoch, 2014; Nožička, 1957). The resulting shortage of wood, contributed to the development of regulations in forest management. As such, the Forest Order for Bohemia and Moravia was issued in 1754 and promoted pine and spruce as suitable species for forest restoration for their rapid growth, easy management and profitability (Filkova et al., 2015). In the following reforestation period during the 19th century, silvicultural approaches adopted management practices from western neighbours and resulted in monocultural regeneration. On sandy soils the pine was preferably planted, however the spruce tolerated and prospered on variety of conditions and subsequently was introduced beyond its natural ecological optimum (Filkova et al., 2015; Nožička, 1957).

While increased temperatures at lower altitudes allow for a prolongation of the growing season of Norway spruce, they also increase tree water requirements. Since lower altitudes generally receive less precipitation, the potential growth advantage of warmer conditions become increasingly constrained by water availability (Tumajer et al., 2017).

2.2 Forest hydrology and precipitation partitioning

Hydrological processes are commonly described using a water balance approach based on the conservation of mass, where changes in water storage are determined by the balance between water inputs and outputs within a defined system (Sutcliffe, 2004). The main inputs in a forest are represented by precipitation and inflow. Since precipitation interacts with the vegetation, this input is further redistributed to several distinct water pathways. This process is regarded as precipitation partitioning. The main components include interception, throughfall, and stemflow (Crockford & Richardson, 2000). Gross precipitation is regarded as above canopy precipitation, but since the interaction with vegetation occurs, net precipitation is used to denote the combined fluxes of throughfall and stemflow. These components are connected to infiltration, outflow, and evapotranspiration, representing the output parts of the forest water balance. The soil environment serves as a reservoir for water storage, providing resources for vegetation (Rodríguez-Iturbe & Porporato, 2007). Individual components of forest water balance will be described in further detail.

2.2.1 Interception

Interception represents the part of gross precipitation that is captured on vegetation and other above ground surfaces, before it either evaporates back to the atmosphere or is transferred further as throughfall or stemflow. In forests, interception is not limited to foliage alone. Water can also be stored on branches, stems, bark, understory vegetation and forest floor (Gerrits et al., 2007). Consequently, the total interception of a forest stand results from several interacting storage surfaces rather than from the tree canopy alone (Van Stan et al., 2020). During small rainfall events, a large proportion of precipitation can be retained by the canopy and subsequently evaporated, meaning that little or no water may reach the soil surface. Interception loss is typically proportionally higher during small and low-intensity rainfall events (Staelens et al., 2008), while larger events tend to produce greater absolute throughfall and stemflow inputs.

However, the magnitude of interception depends on both meteorological characteristics and vegetation. Important meteorological factors include event size, rainfall intensity, duration, wind speed, air humidity and atmospheric evaporative demand. Vegetation factors include canopy density, leaf area, branch angle, bark roughness, surface wettability and stand structure (Crockford & Richardson, 2000). These traits determine how much water can be stored on plant surfaces, how quickly the surfaces become saturated and how efficiently intercepted water is evaporated or redirected toward the forest floor.

Snow interception differs from rainfall interception as snow can adhere to surface in larger amounts and can remain stored in the canopy for longer periods. Part of the intercepted snow may sublimate directly from the canopy,

while another part may unload to the forest floor as meltwater or snow clumps (Hedstrom & Pomeroy, 1998). The evergreen coniferous trees had been found to have a less snow accumulation beneath their canopies when compared to deciduous canopies (Mahat & Tarboton, 2014), reducing the water input to soil. Therefore, snow interception can represent an important seasonal component of precipitation partitioning in cold or mountain environments.

A more subtle source of water is fog interception. However, its importance is recognised particularly in coastal or mountainous environments. Under more continental conditions, its contribution is generally smaller (Sampurno Bruijnzeel et al., 2006). Krecek et al. (2017) reported, that a measurable volumes of fog water were detected above the elevation of 900 m in Jizera mountains.

Seasonality in interception is particularly important in deciduous forests. During the leafed period, foliage increases the available storage surface and generally leads to higher canopy interception (Staelens et al., 2008). In contrast, during the leafless period, canopy storage capacity decreases and a larger proportion of precipitation usually reaches the forest floor as throughfall or stemflow. For example, Mużyło et al. (2012) reported slightly higher throughfall (+3.6%) and stemflow (+1.7%) during the leafless period, resulting in lower interception loss compared with the leafed period. Similarly, in a European beech stand, Staelens et al. (2008) found that foliation significantly increased interception and reduced both throughfall and stemflow for a given rainfall amount. Coniferous forests are often associated with higher annual interception losses than deciduous forests, mainly because evergreen canopies maintain interception surfaces throughout the year (Andreasen et al., 2023). However, this general pattern depends on stand age, canopy density, tree architecture, species composition and climatic conditions.

Since interception is difficult to measure directly, it is commonly quantified using rainfall partitioning measurements, where interception loss is estimated from the balance between gross precipitation, throughfall and stemflow. Although this approach provides the most direct stand-scale estimate, it is labour intensive and spatially limited because both throughfall and stemflow are highly heterogeneous within forest stands (Zhu et al., 2021). Complementary experimental approaches include laboratory rainfall simulations, however these methods usually include only the floor litter (Putuhena & Cordery, 1996), parts of the trees (Holder & Gibbes, 2017) or tree seedlings (Chen et al., 2025). Therefore does not capture the complexity of forest vegetation. Further research focuses on wettability of the leaf surface, that directly affect the canopy water storage. Leaf waxes measured by contact angle of water with the surface (Cape et al., 1989; Holloway, 1969; Papierowska et al., 2018) and microstructures such as trichomes (Brewer et al., 1991; H. Wang et al., 2015) or dust were identified to have a significant effect in this regard (Rosado & Holder, 2013).

For larger spatial scales, remote sensing provides an important way to

characterise vegetation properties relevant to interception (de Jong & Jetten, 2007). Satellite imagery and laser scanning are used to estimate forest structural variables such as leaf area index, canopy height, and seasonality (Baptista et al., 2018; Miralles et al., 2010).

Both kinds of measurements are commonly used in interception models (Muzylo et al., 2009). The physically based Rutter model (Rutter et al., 1971) represents the canopy as a dynamic water storage reservoir, where intercepted water is depleted by drainage and evaporation from wet canopy surfaces. In contrast, the analytical Gash model (Gash, 1979) estimates interception loss at the event scale from gross precipitation, canopy storage capacity, canopy cover, wet-canopy evaporation and stemflow-related parameters.

2.2.2 Throughfall

Throughfall is the portion of gross precipitation that reaches the forest floor either directly through canopy gaps or after being temporarily retained and subsequently released from vegetation surfaces (Crockford & Richardson, 2000; Van Stan et al., 2020). It is therefore closely linked to interception and is controlled by both vegetation traits and meteorological conditions. For liquid precipitation, several forms of throughfall can be distinguished. Free throughfall refers to precipitation that passes through canopy openings without contact with vegetation surfaces. In contrast, canopy drip consists of water that has been intercepted by leaves, branches or stems and is subsequently released as drops. A more detailed classification also includes splash throughfall, which is generated when impacting raindrops release smaller droplets from wetted vegetation surfaces (Nanko et al., 2006). With snow precipitation, the throughfall is differentiated as unloading (solid phase) and melt (liquid) (Levia et al., 2019).

An important characteristic of throughfall is its drop size distribution (DSD), which describes the relative abundance of drops of different diameters. Forest canopies may substantially modify DSD compared with open rainfall. Because free throughfall does not interact with vegetation, its drop size distribution is expected to be similar to that of open precipitation. By contrast, canopy drip often contains larger drops, commonly reaching several millimetres in diameter, whereas splash-generated droplets are typically smaller (Levia et al., 2017). These processes are interconnected, as large canopy-drip drops may produce secondary splash droplets during their passage through the canopy. Changes in DSD are hydrologically relevant because they affect the kinetic energy of water reaching the forest floor, with implications for splash erosion, litter disturbance and infiltration processes (Hall & Calder, 1993; Nanko et al., 2004).

As with the interception the seasonality is important. Levia et al. (2019) reported that the canopy drip volume in conifers accounted for a 51 % while in broadleaves it accounted for 69 %. However in the leafless season the canopy drip of broadleaves reduced to 8% of precipitation volume. Moreover the size of

the canopy drip reduced from 4.32 mm (leafed) to 2.24 mm (leafless). Similarly, (Staelens et al., 2006) demonstrated that the throughfall beneath the canopy of beech dominated forest was spatially heterogeneous and differed in leafed and leafless phenological stages. This behaviour was more prominent in smaller precipitation events.

Throughfall is one of the most spatially heterogeneous components of precipitation partitioning in forests. This heterogeneity in throughfall has been linked to to the spatial heterogeneity of soil moisture (Fischer-Bedtke et al., 2023).

Since the interaction of precipitation and vegetation surface, the chemical composition of the water can be altered. During contact with leaves, branches and bark, water can leach nutrients and organic compounds from vegetation surfaces and wash off dry atmospheric deposits accumulated on the canopy (Van Stan & Stubbins, 2018; Van Stan et al., 2020). As a result, throughfall often contains higher concentrations of dissolved ions, dissolved organic carbon and other solutes than open precipitation. This chemical enrichment can influence nutrient inputs to the forest floor and affect soil chemical processes (Parker, 1983).

A standard for measuring throughfall includes a set of spatially distributed rain collectors installed beneath the canopy. Two methods are used in this regard, a fixed position or a moving (roving) position of rain gauges (Levia et al., 2017; Ritter & Regalado, 2014). While fixed collectors are suitable for capturing the general heterogeneity of throughfall and its connection to temporal, seasonal or spatial change, the roving gauges were found to provide a more representative estimate of stand-level mean throughfall by reducing the influence of local drip points (Zuecco et al., 2014). In order to determine the throughfall fraction of precipitation, the open precipitation needs to be measured as well. Modern indirect methods include optical disdrometers, utilising high resolution camera or laser technology. These approaches allow for not only the quantification of throughfall amount, but also the measurement of drop size distribution and related characteristics such as drop velocity and kinetic energy (Levia et al., 2019).

2.2.3 Stemflow

In addition to throughfall, a smaller but hydrologically important fraction of gross precipitation is redistributed as stemflow. Stemflow refers to the portion of precipitation that is captured by the canopy and subsequently routed along branches and stems to the tree base (Levia & Germer, 2015). Although stemflow usually represents only a minor proportion of total precipitation input at the stand scale, it can generate highly concentrated water inputs near the stem and thereby contribute to the formation of infiltration hotspots (Metzger et al., 2021). A recent global synthesis reported that stemflow accounts, on average, for 5.06% of gross precipitation, although values vary widely across biomes,

ranging from 0.01% to 49.3% (Wu et al., 2024).

The magnitude of stemflow is controlled by both abiotic and biotic factors. Important abiotic drivers include rainfall intensity (Zabret & Šraj, 2021), wind conditions (Van Stan II et al., 2011), and temperature-related effects (Dunkerley, 2014; Wu et al., 2024; Zhang et al., 2021). Biotic factors include bark texture (Livesley et al., 2014), canopy characteristics (Levia et al., 2015), stand density (Metzger et al., 2019) and tree size (Honda et al., 2015). Species-specific differences in stemflow generation have been reported by André et al. (2008). Consequently, the hydrological role of stemflow cannot be described solely by its absolute water volume. Metrics that account for tree size, canopy area, and chemical enrichment are therefore often used to compare stemflow processes among species, individuals, and forest stands.

A funnelling ratio is a metric used to compare stemflow contributions between different species and sizes. It describes the efficiency of crown to capture and subsequently channel the water to the stem (Herwitz, 1986; Levia & Germer, 2015). A study by Siegert and Levia (2014) showed that smaller trees may exhibit higher funnelling ratios, indicating a high efficiency in routing water directly to the basal root zone. This may be particularly relevant for understory trees and forest regeneration, as stemflow can locally enhance water availability near the stem. In connection, a double-funnelling effect is phenomenon of channelling the stemflow water through preferential pathways along tree roots, creating effective water recharge (Johnson & Lehmann, 2006).

Stemflow is also important from a biogeochemical perspective. The enrichment ratio compares the solute concentration or solute fluxes in stemflow with those in incident precipitation. This describes the relative enrichment of stemflow compared to open rainfall, reflecting vegetation leaching or deposition wash-off along flow paths over foliage, branches and stem (Wu et al., 2024). The character of precipitation has been found to have an effect on the nutrient leaching. A study by (Levia & Herwitz, 2000) reported that the enrichment of the precipitation water was significantly more prominent in case of mixed precipitation with multiple freezing and melting cycles, when compared to early spring precipitation. In a following study snow-to-rain events were confirmed as the most prominent (Levia, 2003).

Seasonality further influences stemflow generation, especially in deciduous trees. André et al. (2008) reported higher total stemflow volumes during the leafless period compared with the leafed season. Similar seasonal patterns have also been reported by (Mużyło et al., 2012; Staelens et al., 2008).

Stemflow is commonly measured by capturing water that flows along the tree trunk. A rubber collar or spiral gutter is wrapped around the tree trunk, directing the water to container or tipping bucket. Here, a manual or automatized (B. Turner et al., 2019) detection of volume or mass change is recorded. Because measurements are usually performed only on a subset of trees, the selection of representative individuals is crucial for scaling stemflow from the

tree level to the stand level. Sample trees should therefore reflect the variability in species composition, tree size, bark characteristics, canopy structure, and stand position (Levia & Germer, 2015).

2.2.4 Infiltration and preferential flow

Infiltration is the process by which water enters the soil profile through the surface. This process is governed by several factors, including soil texture, structure, water content and external variables such as topography, soil saturation, and land-use practices (Basset et al., 2023; Hillel, 1998).

Infiltration characteristics are generally quantified by cumulative infiltration, infiltration rate, and hydraulic conductivity (Assouline, 2013; Parr & Bertrand, 1960). While cumulative infiltration represents the total amount of water entering the soil per unit area over time, the infiltration rate reflects the velocity of this process. This is typically expressed in mm/h. Generally, the infiltration rate decreases as soil saturation increases (Wei et al., 2022). Consequently, saturated hydraulic conductivity (K_{sat}) is commonly used as a standard soil hydraulic property for comparing the ability of different soils to transmit water under saturated conditions (Pachepsky & Park, 2015).

The surface soil layer forms a critical boundary, controlling the partitioning of precipitation between surface runoff and infiltration (Horton, 1933). The character of soil cover may substantially alter the infiltration process (L. Wang et al., 2020). As a result of rainfall impact, rapid wetting, and subsequent drying, fine grained soils are prone to form surface crust. The resulting crust represents a layer with distinctly different structural and hydraulic properties, which can significantly reduce infiltration. This is a common issue in agriculture, particularly on bare soils directly exposed to rainfall (Assouline, 2004). Similarly, biological soil crusts are formed by communities of bacteria, algae, lichens, mosses and fungi, which can promote the cohesion and stability of surface soil material. However, their effect on infiltration rate is variable (Kidron, 2019).

While the soil matrix flow is primarily determined by the soil texture and structure, the presence of preferential pathways can significantly enhance flow rates (Jarvis et al., 2012). Structural heterogeneities such as organic debris (e.g. twigs, fragments of bark, foliage) or soil microbiota, are know to affect the preferential flow (Jačka et al., 2021).

Soil organic matter can improve infiltration, however it may also contribute to water repellency (also hydrophobicity). This is well-documented for vegetation rich in hydrophobic compounds, such as Eucalyptus (Walden et al., 2015) or Pinus species (Orfanus et al., 2008). A seasonal variation in hydrophobicity induced by trees in top 10 cm was observed with a significant increase in summer months (Buczko et al., 2006).

Root systems differ among tree species in their morphology, spatial distribution and functional roles. In general, roots provide anchorage and mechanical stability, take up water and nutrients, and serve as storage for carbon (Brunner

& Godbold, 2007). Roots can be divided into coarse structural roots and fine roots (feeders). Coarse roots mainly provide mechanical support and long-term carbon storage, whereas fine roots are primarily responsible for water and nutrient uptake (Perry, 1989). Through their growth, turnover and decay, roots can contribute to the formation of soil macropores. The rooting depth of trees is affected by soil properties, as compact soils can be restrictive for root development (Crow, 2005). Distinct tree species have characteristic root systems, the main representatives are: taproot system (English oak, Scots pine, silver fir), heart root systems (birch, beech, larch) and surface root systems (ash, aspen, Norway spruce) (Büsgen, 1929; Crow, 2005).

Field based methods of infiltration measurement typically involve ponding water over a defined area of soil surface and subsequent monitoring of its infiltration into the soil over time. The decrease of water level is recorded. With a constant head, the water is maintained at certain level. For this a single or double ring infiltrometers are generally used (Verbist et al., 2010). To determine saturated hydraulic conductivity at different depths within the soil profile, excluding the surface layer, a Guelph permeameter can be used to perform in situ measurements in a borehole (Dolezal et al., 1997). To exclude the macropore flow a tension infiltrometers are used. In principle a negative pressure head is applied to soil interface, therefore the capillary forces of soil are required to draw the water. Using this method a proportion of preferential flow by macropores may be determined (Schwärzel & Punzel, 2007).

2.2.5 Transpiration and evaporation

Transpiration is the process of releasing water vapour from plants to the atmosphere. It represents a major pathway and therefore forms an important component of the forest water balance (Kozlowski & Pallardy, 1997). While transpiration refers to water taken up by roots and released by vegetation, evaporation describes the conversion of liquid water to water vapour from wet surfaces, soil and open water. Evapotranspiration integrates both transpiration and evaporation and thus represents the total water vapour flux from vegetated land surfaces to the atmosphere (Kool et al., 2014).

Most transpiration occurs through stomata, located mainly on the assimilation organs of plants. Stomata form a gate that regulates the exchange of water vapour and carbon dioxide between the leaf and the atmosphere (Hetherington & Woodward, 2003). A smaller fraction of water loss occurs through the plant epidermis, referred to as cuticular transpiration. Under normal conditions, cuticular transpiration usually represents only a minor fraction of total transpiration (Burghardtt & Riederer, 2003).

Transpiration is closely linked to essential plant physiological functions. The transpiration stream supports the transport and supply of water and dissolved nutrients from the soil to the canopy, contributes to the maintenance of plants body structure and through the dissipation of energy to latent heat provides

evaporative cooling of leaves and needles. At the same time, transpiration is closely connected with photosynthesis, since stomata are responsible for uptake of CO_2 from atmosphere. This creates a fundamental trade-off between carbon assimilation and water conservation (Matthews et al., 2017).

The rate of transpiration is controlled by the interaction between atmospheric demand, soil water availability, and plant physiological regulation. Under sufficient soil water availability, transpiration is mainly driven by available energy, radiation, air temperature, humidity, wind speed, and vapour pressure deficit (Kozlowski & Pallardy, 1997).

Soil water availability becomes increasingly important during dry periods. As the soil dries, root water uptake is constrained by declining soil water potential and decreasing hydraulic conductivity of the soil plant continuum (Lobet et al., 2014). Under drought, transpiration may therefore be reduced or halted even when atmospheric demand remains high. This can increase leaf temperature and contribute to heat stress, since the cooling effect of transpiration is weakened (Teskey et al., 2015).

Species-specific traits further modify the duration, timing and intensity of transpiration (S. Gupta et al., 2018). Since the foliage of evergreen trees does not go through senescence in autumns, the transpiration may under favourable conditions continue even in the winter and spring period. Deciduous species are restricted with the main transpiration flux until the foliage development (Rötzer et al., 2017), however in general, compensate this with a higher canopy conductance.

Transpiration can be estimated at several spatial scales. At the leaf level, gas exchange or porometer measurements can quantify stomatal conductance and leaf transpiration (N. C. Turner, 1991). At the tree level, sap flow measurements are widely used (Granier et al., 1996). These methods do not measure transpiration directly, but estimate xylem water flow, commonly in the stem, which is then used as a proxy for tree water use. Thermal based techniques derive sap flux density from heat transport in the conducting xylem (Kool et al., 2014). Although sap flow measurements are broadly used, they are affected by uncertainties related to sensor placement, radial variability of sap flow, tree water storage, and scaling from point measurements to stand level transpiration. Granier et al. (1996) reported that a 5-10 sapflow sensors in general provide a solid estimate of stand transpiration.

At the stand scale, eddy covariance is commonly used to estimate water vapour exchange between the ecosystem and the atmosphere. This method is generally used to measure the integrated transpiration and evaporation when placed above the canopy, however studies also used it as an under canopy estimation of evaporation (Kool et al., 2014).

2.3 Tree-traits mediated hydrology

Components of forest hydrology distinctly differ with respect to a tree species. Since different tree species have different characteristics of crown architecture, root system, phenology and water requirements, these contribute to differences in precipitation partitioning and water requirements. Three selected tree species covered in this thesis will be further introduced by its ecological characterization and hydrologically relevant literature on their specific tree traits with connection to forest hydrology. While beech and spruce trees are commonly used in ecohydrological studies as contrasting tree species, the hydrology of larch trees is much less explored. Moreover, he main focus is on the growth, rather than the effect on the surrounding environment. In this regard, an evident lack of knowledge was identified.

2.3.1 European Beech (*Fagus sylvatica*)

Beech is a widely spread native European deciduous tree. It is a large broadleaf tree, capable of reaching 50 m in height, with smooth silver-grey bark and a dense crown architecture (von Wuehlisch, 2008). In contrast to many other European tree species, beech can maintain relatively high growth rates until late maturity and may reach a lifespan of 150–300 years (Houston Durrant et al., 2016). In lowlands, its main competitors are oaks (Packham et al., 2012).

Its native distribution spans from the south of Scandinavia to the Mediterranean sea (Fig. 2.2). However, at the southern range, the beech usually occurs in altitudes over 1000 m (Houston Durrant et al., 2016; von Wuehlisch, 2008). In the northern part of its distribution, beech is mainly limited by growing-season length and temperature conditions, whereas towards the southern and south-eastern margins of its range, high summer temperatures and limited moisture availability become increasingly important constraints (Bolte et al., 2007; Fang & Lechowicz, 2006).

Ecologically, European beech is characterised by high shade tolerance, which is its main competitive advantage. Once established, beech can strongly reduce light availability in the understory, thereby suppressing less shade-tolerant species and reinforcing its own regeneration (Packham et al., 2012). Although beech grows on a relatively wide range of soils, it performs best on fresh, well-drained and moderately fertile sites where roots can penetrate easily. In contrast, it performs poorly on very dry, compacted, waterlogged or regularly flooded sites (von Wuehlisch, 2008).

The heart root system with predominantly downward roots at about 45° angle are not spreading very far from tree trunk (Rust & Savill, 2000). Recent study by Pietig et al. (2026) reported that in deep sandy soil, the water absorbing fine roots (< 2mm) of mature beech trees reached up to a depth of 380 cm. However, the rooting depth is variable based on local conditions and is usually much smaller (Crow, 2005; Leuschner et al., 2001). On a compacted, high

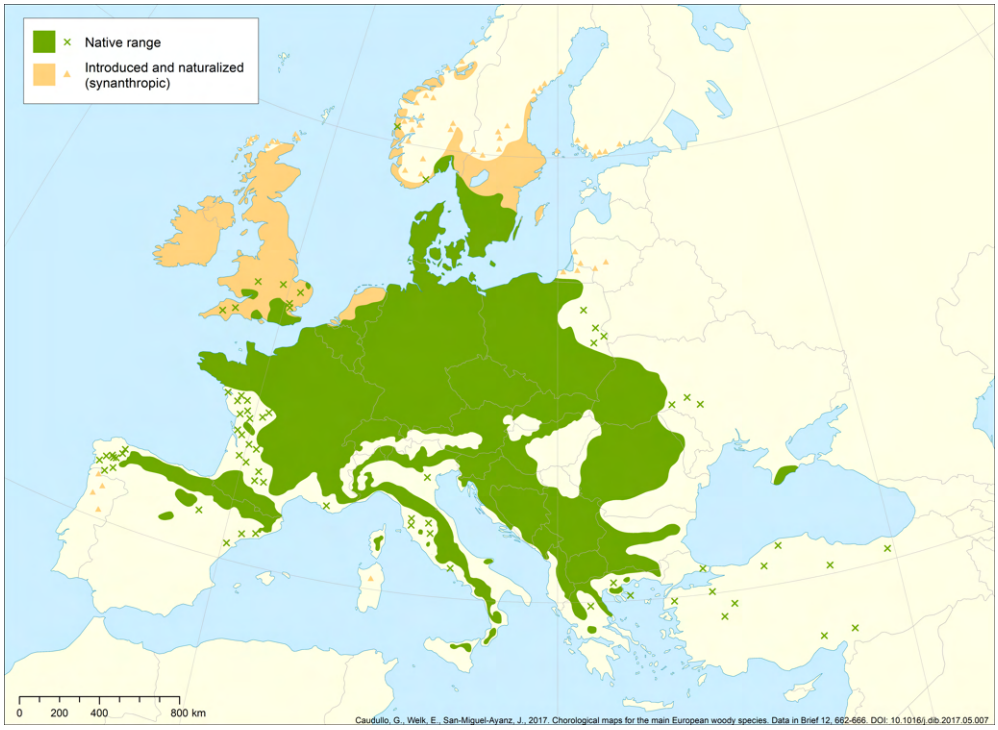


Figure 2.2: The spatial distribution area of European beech. The native range is depicted in green colour, while the introduced is in brown. Adapted from Caudullo et al. (2018).

silt content cambisol, Schwärzel et al. (2009) reported the maximum rooting depth of beech in 80 cm, while 90% of the roots were present in the top 45 cm. Other resources classify the root system of beech as relatively shallow (Houston Durrant et al., 2016). Since its abundant production of high quality leaf litter, beech significantly contributes to soil formation and protection (Houston Durrant et al., 2016; von Wuehlisch, 2008).

Despite its high competitive ability under suitable conditions, it is sensitive to late spring frost resulting in damage of assimilation organs (Houston Durrant et al., 2016; Packham et al., 2012). Recent studies also indicate that drought and heat stress may increasingly limit beech growth and vitality under climate change, particularly in lowland and drought-prone regions (Martinez del Castillo et al., 2022).

In the mean annual proportion of precipitation partitioning a dominant position has throughfall with 71%, followed by interception 21% and smaller although important part in stemflow 8%. However these proportions depend on the rain event characteristics, such as rain duration, total amount and intensity, and also on the season. In leafed period the throughfall is decreased to 63% as opposed to 80% in winter. Same goes for the stemflow, in vegetation period is reduced to 6.4%, while in winter reaches to 9.5% (Staelens et al., 2008). The rainfall threshold for generating the stemflow in beech is low, accounting for 3.4 mm during the leafed season and 1.5 mm in the leafless season. Compared to oak trees this was four time lower in leafless stage and more than three times lower in leafed season (André et al., 2008).

Rainfall simulations showed, that the majority of water contributing for the stemflow is generated in the centre of crown, while the edge branches contribute only partially (Frischbier & Wagner, 2015). This illustrates that the crown architecture has direct effect on the precipitation partitioning and possibly to a soil water recharge. Metzger et al. (2021) found that stemflow infiltrating at the base of tree trunk creates an infiltration hotspots with chemically and physically altered properties by the flowing water. These altered properties enable the water to infiltrate easily. Schwärzel et al. (2012) using dye tracer provided an evidence that beech trees are capable of the double-funnelling effect, enabled by their crown and rooting architecture. This illustrates the exceptional ability of beech trees to concentrate and channel water trough preferential pathways directly to its roots.

While in the winter the throughfall and stemflow increases, the opposite is true for the canopy interception, as in the full leaf accounts for 30%, nearly a third of the precipitation and in the winter about 10% is intercepted (Staelens et al., 2008). Interception in beech forest is a significant part of water balance, due to a dense canopies and high abundance of tree litter. Together these account for 26% in winter and 36% in summer. However, while the storage capacity of forest floor is seasonally constant (1.8 mm), the storage capacity of canopy alters in seasons due to foliage changes (0.1 mm winter, 1.2 mm

summer). The capacity of forest litter increase only briefly after the leaf fall, however is soon reduced by the rain and snow precipitation (Gerrits et al., 2010). The significant winter reduction in interception allows, the recharge of soil water is promoted by the deciduous nature of beech.

Intercepted water is further released or evaporated. For canopy interception the evaporation accounts for 18% of in summer and 5% in winter. The forest floor evaporation is estimated to 22%, excluding the snow phase (Gerrits et al., 2010).

The transpiration rates of beech trees are high. Hietz et al. (2000) reported that it can be up to 5 times higher in beech when compared to spruce. While in the summer drought of 2006, the spruce forest decreased its transpiration rate, the beech forest did not show a significant reduction, this was attributed to the deeper rooting zone, reaching for more water reserves (Schwärzel et al., 2009). While this may benefit in increase in growth and vitality of beech forest, on the other side the high summer transpiration rates may consume a considerable amount of water and therefore contribute to intensifying of summer drought impact (Zelíková et al., 2025).

Beech trees are considered having anisohydric strategy, therefore they maintain a high transpiration rate until the point of hydraulic failure. The crown dessication in the summer is the manifestation of such behaviour, where part or a whole crown is restricted of water. In Croatia, a significant increase of the mean percentage of defoliation in beech forest during the 1996 - 2017 war reported (Ognjenović et al., 2022). This illustrates the rising water requirements on beech forest.

The onset of sap flow and thus transpiration is closely linked to leaf development. Urban et al. (2015) reported that the first measurable sap flow in beech was at 50% first-leaves phenophase, while maximum sap flow occurred in June after full leaf expansion and under non-limiting soil water conditions. Granier et al. (2000) showed that stand transpiration in a mature European beech forest increased rapidly after budbreak and reached its maximum values approximately 28 days after budbreak. Total stand transpiration reached about 253–256 mm, while total evapotranspiration accounted for 338–351 mm during the leafy period from early May to late October. Other authors reported even higher values, however the actual rate depends strongly on external factors such as soil moisture conditions (Nalevanková et al., 2020). When compared to spruce stand, beech stand due to its phenology have limited window for transpiration. Rötzer et al. (2017) reported that transpiration reached its maxima in summer. However, while in this period, transpiration in beech (199 mm) was higher than in spruce (181 mm), across the annual course the total transpiration was higher in spruce (396 mm) than in beech (343 mm). This was attributed to the longer transpiration window of spruce.

Despite its high importance in European forest, several studies repeatedly suggest its drought vulnerability (Leuschner, 2020). Under drought beech

trees are described to limit their growth, crown dessication and premature leaf senescence (Chakraborty et al., 2021; Walthert et al., 2021). In 2019 on average 21% of beech crowns was impacted by some degree of defoliation, however among the main European broadleaved tree species, beech had the lowest mean defoliation. An increase in the past 20 years is however observed (Michel et al., 2020).

The intensification of precipitation altered by climate change strongly affected the spatio-temporal distribution of precipitation partitioning in beech forest. Therefore with the change in climate we may expect that a significant part of European´s forest could be affected by change in water fluxes (Drollinger et al., 2025).

Future projections indicate that European beech may shift its potential distribution north-eastwards and towards higher elevations (Liepiņš & Bleive, 2025). However, this potential expansion is unlikely to translate directly into realised range expansion, because beech migration is slow and constrained by habitat fragmentation, demographic processes and increasing climatic variability (Saltré et al., 2015). At the same time, recent modelling studies project declining growth and productivity across large parts of the current range, particularly in warmer and drier lowland regions of Central and Southern Europe (Martinez del Castillo et al., 2022). Therefore, although beech is often considered a promising alternative to declining Norway spruce, its future performance in drought-prone Central European sites remains uncertain and dependent on local water availability.

2.3.2 European Larch (*Larix decidua*)

European larch is the only deciduous conifer native to Europe. Its natural distribution is relatively small and fragmented, mainly concentrated in Central European mountain regions, particularly the Alps, Sudetes and Carpathians, with isolated lowland occurrences in southern Poland (Fig. 2.3). Although its native range is limited, European larch has also been planted outside its natural distribution, especially in Western and Central Europe. Its long-lived nature, spanning up to 1000 years, makes larch particularly suitable for dendrochronology and study of past climate (Da Ronch et al., 2016; Matras & Pâques, 2008).

The species is a light-demanding and fast-growing pioneer that spreads on open or disturbed sites. In the Alps, it grows particularly well at elevations around 1400–1500 m, but its overall altitudinal range is broader reaching up to 2500 m. At higher elevations, where competition from shade-tolerant species is reduced, it may form pure stands, however at lower elevations and in mixed forests it is often outperformed by Norway spruce (Picea abies) or silver fir (Abies alba) (Da Ronch et al., 2016; Matras & Pâques, 2008).

European larch can grow on a wide range of soils, but it prefers well-structured, aerated, and well-drained soils, therefore waterlogged conditions are

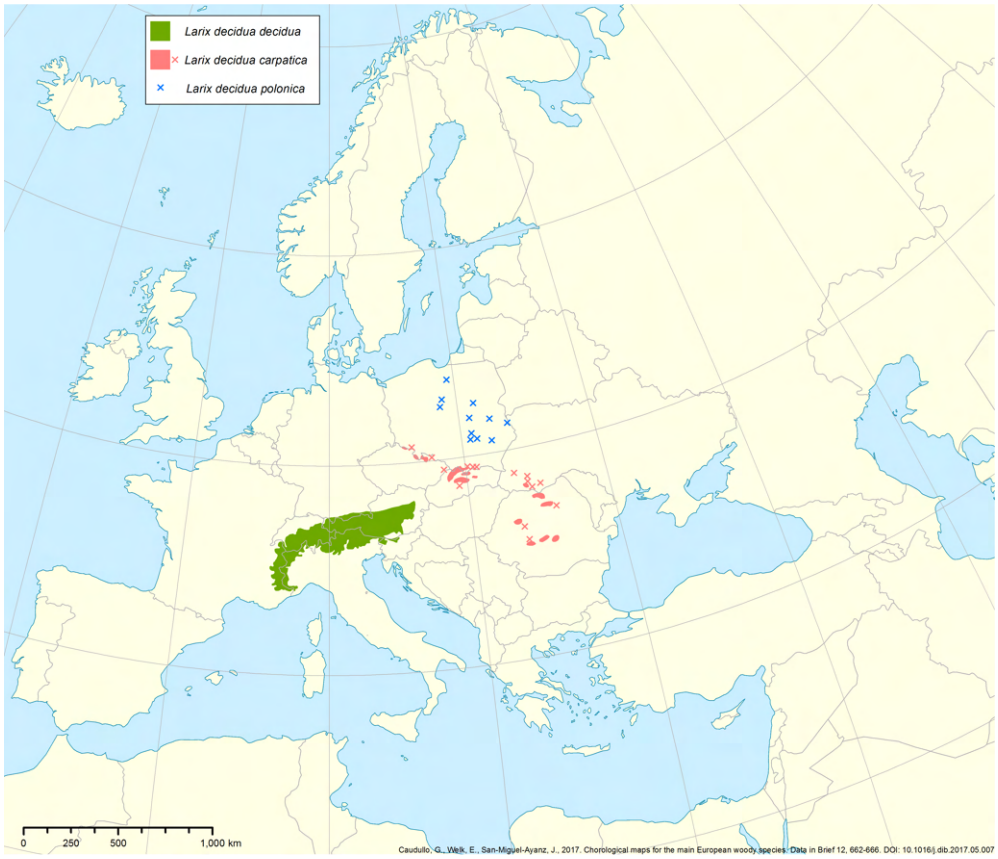


Figure 2.3: The native distribution of European Larch. Three subspecies are marked. In green Larix decidua decidua, in pink Larix decidua carpatica and in blue isolated occurences of Larix decidua polonica. Adapted from Caudullo et al. (2018).

unfavourable (Da Ronch et al., 2016; Matras & Pâques, 2008). Its heart-root system may contribute to relatively good resistance to windthrow (Da Ronch et al., 2016). The deciduous nature represents an adaptation to cold continental and alpine climates, as needle shedding before winter reduces the risk of foliage desiccation when water uptake is limited by frozen soils (Da Ronch et al., 2016). Although deciduous, larch shares several traits of crown architecture, leaf morphology and water-conducting anatomy with evergreen conifers (Gower & Richards, 1990).

The deciduous habit strongly affects the seasonal pattern of carbon uptake and water use. Compared with evergreen conifers and similar to other deciduous trees, larch has a shorter active vegetation period and therefore needs to maintain high physiological activity during the growing season. This is reflected in higher assimilation rates per unit leaf area, when compared to evergreen spruce. On average the assimilation rates in larch trees were observed to be 40% higher when compared to spruce trees. Although the length of this period was in larch substantially shorter (Matyssek, 1985). Spring phenological development is mainly controlled by temperature, whereas autumn senescence is more constrained by photoperiod (Migliavacca et al., 2008). Needle development usually precedes stem growth by several weeks (Moser et al., 2010), therefore a lag in the water requirements and tree growth is present.

Only limited knowledge is available for hydrological processes in larch stands as the main focus of studies is on tree growth, sap flow measurements or dendrochronology of past climate. While water availability is often mentioned as a key factor for its physiological functions and growth, the actual soil conditions are missing. Moreover, most of the studies focus on larch in its native mountainous environment, and comparably less is known about larch trees grown in lower altitudes.

European larch is seen as a potential alternative to Norway spruce in Central Europe (Zeidler et al., 2022). However recent studies repeatedly showed that European larch can be drought-sensitive. This primarily covers the negative responses of growth (Danek & Danek, 2022; Lévesque et al., 2013). Irrigation-exclusion experiments also suggest limited recovery after drought compared with more drought-tolerant conifers - Douglas fir and black pine. Moreover, the larch was reported to lack the ability to recover from drought (Eilmann & Rigling, 2012). Charlet de Sauvage et al. (2023) confirmed the sensitivity to drought of larch when compared to Douglas fir and silver fir, however in this case all tree species were able to recover within two years after severe droughts of 2003 and 2018. This suggest the need of more context in the study of drought response of larch. Recent experimental evidence indicates that low soil water availability, high temperature and vapour pressure deficit in late spring can increase the mortality risk (Sagar et al., 2025).

Transpiration in larch trees is highly connected to actual weather conditions as high fluctuations in daily sap flow values, closely related to weather conditions

has been observed (Anfodillo et al., 1998). Further the reduction in sapflow was observed under drought. However, since larch trees are considered as anisohydric, it does not restrict its stomata under drought conditions and therefore maintains a high transpiration rates even under reduced water availability (Anfodillo et al., 1998).

In larch trees, twice as much precipitation was needed to produce a stemflow when compared to beech and spruce trees. However, the stemflow in larch stands was only minor, resulting in a relatively uniform distribution of precipitation on forest floor (Reynolds & Henderson, 1967). This is in agreement with observation by Cape et al. (1989) who reported a very low stemflow proportion 1-4% of gross precipitation and conversely a high throughfall proportion of 73-87%. This supports that precipitation is not very concentrated by the larch trees and contributes to rather uniform water recharge. The seasonality in larch was reported to have only a minor effect, which was more pronounced in the case of smaller storms, however negligible in the case of larger precipitation events (Reynolds & Henderson, 1967).

Larch trees were described to develop a deep rooting system, enabling the water usage from groundwater when more shallow level of water are insufficient (Valentini et al., 1994). This suggest an adaptability to local conditions, however it is expected to be site specific.

As fast growing trees, larches are associated with high transpiration rates during summer, similar to deciduous broadleaved species. Although their deciduous seasonality may decrease interception in winter and limit water use, they seem to lack effective water recharge. This may make them less suited to future climatic patterns, characterized by increased temperatures and uneven precipitation distribution.

2.3.3 Norway Spruce (*Picea abies*)

Norway Spruce has a long tradition of cultivation across the continent. Up to these days, it has gained a dominant position in economic and production sectors. It is widely used in construction, paper manufacture and furniture (Skrøppa, 2003). Consequently, its current distribution is a way out of its native spread. As a natively a mountain species, it used to dominate boreal forests of northern Europe and higher elevated locations in Central and Eastern Europe (Fig. 2.4). Starting the 18th century the spruce become widely cultivated across western and Central Europe moving even to lower altitudes. Currently its range covers even low altitudes in western and central Europe (Caudullo et al., 2018).

It is a large coniferous tree with evergreen foliage, growing up to 60 m. Its life span is generally around 300 years. Norway spruce is a shade tolerant, growing on most soils, however does not tolerate well waterlogging or summer droughts (Caudullo et al., 2018). Spruce tends to grow on acidic soils and further contribute to increase the acidity of the soil (Augusto et al., 2002). In general, it is described as shallow rooting, with laterally spread roots. However the

rooting depth depends also on local conditions (Puhe, 2003). Schmid and Kazda (2002) showed that in spruce monoculture, large roots (>2 cm in diameter) were limited to the upper 20 cm on stagnic cambisol and to the upper 40 cm on podsol cambisol. Although smaller roots were observed down to 1 m, the total root biomass generally declined with depth. In mixed spruce-beech stands, spruce roots were even more concentrated in the upper soil layers, while beech roots occupied deeper parts of the soil profile. This illustrates the belowground niche partitioning through vertical root stratification, that have been observed in mixed forests (Bolte & Villanueva, 2006).

Evergreen character forms an all year interception, when compared to deciduous species, during winter period it restrict the water recharge from snow precipitation (Zelíková et al., 2025). However, this interception occurs year round and can account for a substantial part of the precipitation budget. Puhe (2003) found that the total interception of spruce forest in the growing season accounted for 34.5% of precipitation, while the mean value of the interception capacity was reported as 2 mm. This is in alignment with (Grundmann et al., 2024), who reported mean canopy storage for young spruce 2.84 mm and mature spruce 2.79 mm.

In connection, Schume et al. (2004) reported decreased water content under spruce trees attributed to interception in early spring. However, other studies suggest that this difference could also origin from an rehydration or onset of early spring transpiration (Kuželková et al., 2024; Rötzer et al., 2017; Turcotte et al., 2009). In Switzerland the annual interception both, the young (68 %) and mature spruce (61 %) trees exceed the interception in beech (53 %) forest. While in the even-based scale the mature spruce (57 %) and beech (58%) had similar values, the young spruce (63 %) had even larger (Grundmann et al., 2024).

Stemflow in spruce trees represents a relatively small fraction. (Dohnal et al., 2014) reported that stemflow in mature spruce trees did not exceed 1% of precipitation from open area. Since its small contribution to precipitation partitioning, some studies even does not include the measurement of spruce stemflow to its water balance (Berger et al., 2008). The crown architecture in spruce produces lateral flow at the outer crown, therefore restricting the stemflow generation (Frischbier & Wagner, 2015). However the precipitation water is concentrated in drip zone at canopy periphery instead (Bartík et al., 2016). In this pathway it will be counted as a throughfall.

Throughfall in spruce stands represents a dominant fraction of net precipitation. Dohnal et al. (2014) reported a high spatial variability in throughfall on a event scale, however this variability was stable across seasons. Frischbier and Wagner (2015) reported a throughfall of 57.2 % in spruce about 6 % less than in beech. Viville et al. (1993) reported throughfall in mature spruce trees in summer 65.3 %.

In general spruce is considered as following isohydric strategy, therefore

stomata regulation under prolonged drought. However a distinct response to drought is observed for individuals from different locations with contrasting conditions (Jamnická et al., 2019). This illustrates that the drought reaction mechanism is adaptive to a local conditions. However the actual transpiration rate highly depends on the soil moisture availability (Střelcová et al., 2013).

While beech and oak trees predominantly use the winter water in mid summer transpiration, the spruce have a more diverse source (S. T. Allen et al., 2019) This pattern may indicate that spruce had already depleted part of the winter-recharged soil water storage earlier in the season and therefore relied more strongly on water supplied by later precipitation events during summer.

Under prolonged drought, the tree is increasingly vulnerable to secondary pathogens. In past decades a sings of vulnerability of spruce monocultures multiplied. Twenty years ago a windstorms were reported as the main disturbance threatening the forests. In more recent days the most relevant is drought. As such, the most pronounced is bark beetle, that in recent decade showed a massive outbreak, resulting in a wide spread mortality and damage across Central Europe.

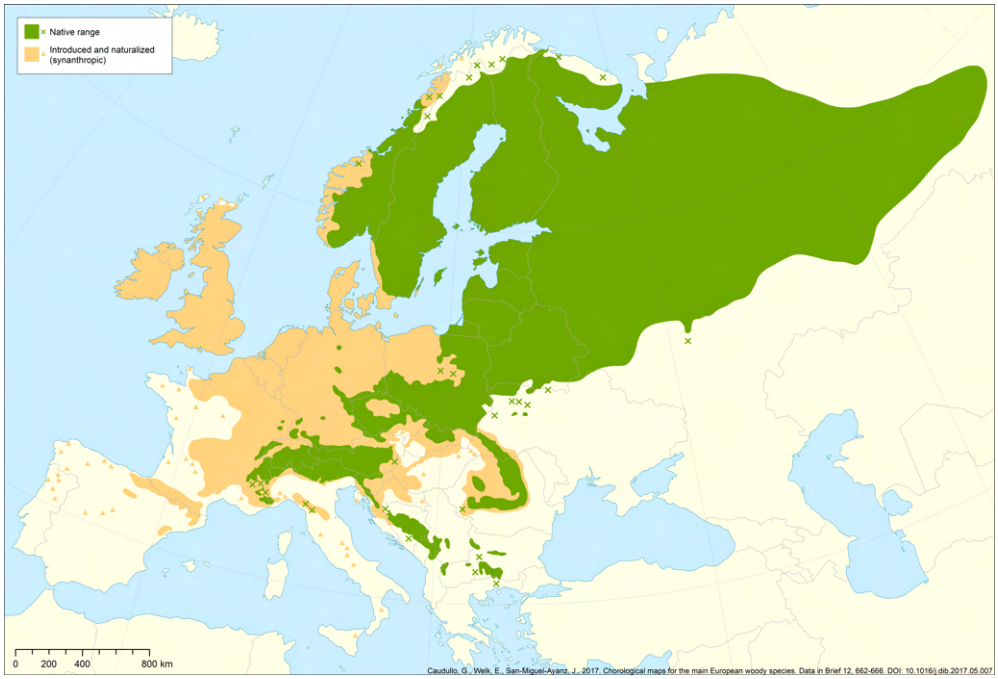


Figure 2.4: The spatial distribution of spruce forest. The native range is depicted in green and the introduced in brown. Adapted from Caudullo et al. (2018).

2.4 Soil and water

Soil represents a major terrestrial water reservoir. It captures and stores precipitation inputs and subsequently releases them as a continuous supply to vegetation (Kutílek, 1978). A surface soil layer represents active interface between atmospheric water input, vegetation demand and hydrological redistribution (Lin, 2010), therefore its character has an influence to local water balance. Soil properties has significant effect on the water balance by distinct textural and structural characteristics (Kutílek & Nielsen, 1994).

In forest ecosystems, apart from the effect on precipitation partitioning, the soil properties are further modified by tree species through their litter and root systems. These may alter the hydraulic properties of soil such as retention (Ilek et al., 2015) and infiltration (Jačka et al., 2021). As a result, the same precipitation event may produce differences in soil water response under distinct forest stands, depending on how water is redistributed before and after reaching the forest floor.

2.4.1 Soil texture, structure and porosity

Soil is a polydisperse system of soil particles and pores, that are filled with air and water (Kutílek & Nielsen, 1994). The size and proportion of individual soil particles is described by soil texture. Several systems are used to classify soils by their texture into distinct categories. Perhaps the most widely used classification system is that of the United States Department of Agriculture (USDA). Although, other systems are in use, therefore a discrepancies in soil comparison may arise (Corral-Pazos-de-Provens et al., 2022).

According the USDA the main division of soil particles distinguishes between the fine earth fraction with a diameter of less than 2 mm and gravel exceeding 2 mm in diameter. The fine particles are further divided in the sand (2 - 0.05 mm), silt (0.05 - 0.002 mm) and clay ($<$ 0.002 mm). The proportion of those three main components differentiate a soil textural class (Fig. 2.5) (Soil Survey Staff, 1993), which are further reflected in soil hydraulic properties (Hillel, 1998). As the differences in soil texture significantly affect both soil retention and infiltration, it subsequently determines the local soil water regime and vegetation. While courser sandy soils tend to have a high infiltration characteristics, it is not able to retain much water by capillary forces. On the other hand the fine-grained clayey soils tend to restrict the soil infiltration and recharge. While it may retain a comparably more water, much of it is tightly bounded, restricting the availability for plants (Hillel, 1998; Kutílek & Nielsen, 1994).

Individual soil particles often merge in larger clumps, referred to as aggregates. These form a soil structure. While clay particles naturally adhere to each other forming a natural glue, sandy soils do not tend to form aggregates. Such soils are are denoted as structureless (also single grained) (Hillel, 1998).

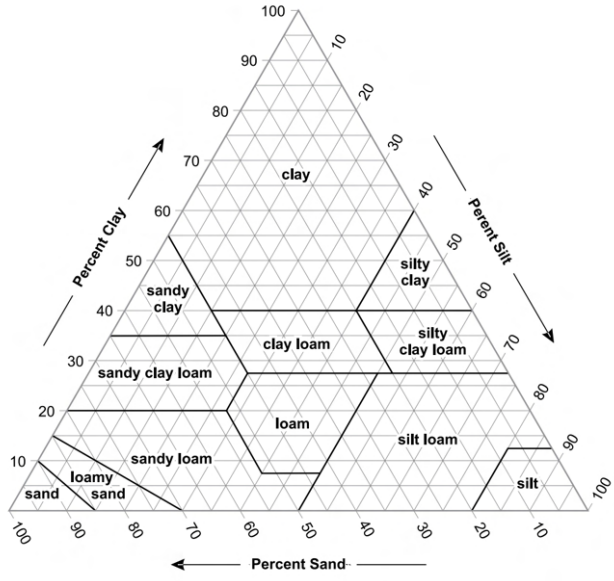


Figure 2.5: Soil class classification triangle. Adapted from USDA (Soil Survey Staff, 1993).

Soil structure further reflects in hydraulic properties of soil matrix. Soil organic matter supports the clumping of soil particles, and contributes to improving the structural properties of soil. The depletion of soil organic matter has been associated with degradation, decreased fertility and increased erosion (Bronick & Lal, 2005).

Soil porosity is defined as the proportion of pore space within the total volume of a soil sample. It varies among soils depending on their texture, structure, organic matter content, and degree of compaction. The porous space forms a reservoir for precipitation. Depending on the conditions, the pores might be filled with air or water continuously transiting between those states (Kutílek, 1978). Porosity is reflected in the hydraulic properties of soil. Large pores, commonly referred to as macropores, enable rapid water movement and facilitate infiltration and drainage. However, they can retain relatively little water since capillary forces are weaker than in smaller pores. In contrast, micropores conduct water slowly but can retain higher amount (Hillel, 1998).

To describe and compare soil samples a bulk density is commonly used as a basic physical characteristic. It is defined as the mass of dry soil divided by the total volume of the soil sample, including both solids and pore space (Kutílek & Nielsen, 1994).

2.4.2 Organic matter

Forest soils are rich in organic matter due to the increased input of vegetation litter. However, the effect of tree litter on physical, chemical and biological characteristics is mostly pronounced in topsoil layer (Augusto et al., 2002). The character of vegetation contributes to a formation of soils. The organic soil horizon (O) is vertically divided into three main layers. Litter (L), fermentation (F) and humus layer (H). The first layer consists of non decomposed fresh vegetation litter, middle layer forms a partially fermented fragmented matter, where its origin is still recognisable. The last layer forms a transition to mineral soil with completely transformed organic matter (Green et al., 1993).

Tree species contribute to the formation of humus, actively affecting its soil environment. While deciduous tree species provides a regular source of tree litter, under evergreen trees the organic matter input is limited. This further mirrors in the rate of decomposition and soil formation. The tree litter rich environment under the deciduous trees promote the emergence of mull humus layer, characterized by a nutrient-rich basic environment with a significant presence of soil fauna. This further shape the character and properties of soil, by their activity and decomposition of organic material. For example as described by (Frouz et al., 2013) the presence of earthworms contributes to the soil formation and their burrows can significantly enhance the preferential flow and therefore promote the infiltration of water (Jačka et al., 2021).

As opposite, the mor humus form is characterised as nutrient poor, with a predominant slow decomposition by fungi. Since the slow rate of decomposition, this form of soil humus typically develops under coniferous evergreen trees, where the input of litter is less frequent. This environment is typically acidic, contributed by the litter source it self and the slow fungal decomposition, enabling the build up of organic acids. As an intermediate transitional type of soil humus, the moder is developed under both coniferous and deciduous forests. This environment serves both microbial and the fungal decomposition in cooperation. However, other characteristics such as properties of mineral soil, climate and water regime contribute to differentiation of humus form (Green et al., 1993).

2.4.3 Soil water content and soil water storage

Soil serves as a reservoir of water and nutrients, supporting their supply to vegetation. The amount of water contained in soil is referred to as soil water content or more generally soil moisture. Soil water content can be expressed on either a gravimetric or volumetric basis. Gravimetric water content is defined as the mass of water relative to the mass of oven-dry soil (Eq. 2.1) (Kutílek, 1978).

$$w = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} = \frac{m_w}{m_{\text{dry}}} \tag{2.1}$$

where w is the gravimetric water content ($\mathrm{kg\,kg^{-1}}$), m_{wet} is the mass of the wet soil sample, m_{dry} is the mass of the oven-dry soil sample, and m_w is the mass of water in the sample.

Volumetric water content represents the volume of water per volume unit of soil. Volumetric water content is most commonly used since it can be directly converted into soil water storage by multiplying it by the thickness of the respective soil layer (Eq. 2.2) (Kutílek, 1978).

$$\theta = \frac{V_w}{V_b} \tag{2.2}$$

where θ is the volumetric water content ($\mathrm{m^3\,m^{-3}}$), V_w is the volume of water, and V_b is the total bulk volume of the soil sample, including both soil solids and pore space.

For a continuous soil profile, soil water storage is defined as the integral of volumetric water content over soil depth (Kutílek, 1978). In practice, soil water content is usually measured at discrete depths, representing a middle of individual soil layers. The integral is therefore approximated by multiplying the representative volumetric water content of each layer by its thickness and subsequently summing the water storage of all layers (Eq. 2.3) (C. Wang et al., 2026).

$$SWS = \sum_{i=1}^{n} \theta_i \Delta z_i. \tag{2.3}$$

where SWS is the total soil water storage in the soil profile (mm), θ_i is the representative volumetric water content of the i-th soil layer ($\mathrm{m^3\,m^{-3}}$), Δz_i is the thickness of the i-th soil layer (mm), i denotes the individual soil layer, and n is the total number of soil layers included in the calculation.

Various methods are used for determining soil water content. A direct gravimetric method involves collecting a soil sample and determining its water content based on the mass loss after oven drying. Although gravimetric measurement is commonly used as a reference method, destructive sampling and time consumption limits its suitability for continuous long-term monitoring. Therefore, soil water content is frequently estimated using indirect methods based on physical properties that vary with the amount of water present in the soil (Kutílek, 1978). Because these methods do not measure water content directly, a calibration relationship is required to convert the measured sensor response into soil water content (Jačka et al., 2023).

Many commonly used indirect methods are based on the dielectric properties of soil. The relative dielectric permittivity of air is approximately 1, while most soil minerals account for values of approximately 3–7. However, liquid water

has a much higher relative permittivity of approximately 80 at room temperature. Consequently, changes in soil water content strongly affect the dielectric permittivity of the soil sample (Robinson et al., 2003). This relationship is used by time domain reflectometry (TDR), time domain transmission (TDT), frequency domain reflectometry (FDR), and capacitance methods to estimate volumetric soil water content.

While soil water content describes the quantity of water present in soil, it does not directly indicate the availability of water, as a different textural and structural characteristics contribute to a differences in usability by plants (Kutílek & Nielsen, 1994). Therefore soil moisture measurements are often complemented by measures of soil water availability.

2.4.4 Soil water potential

Soil water potential denotes the energy state of a unit of soil when compared to a reference level. The difference in potentials is used to describe the soil water movement in a soil. The direction of movement is from the place of higher potential to an area of lower potential (Kutílek, 1978).

Total potential consists of several partial potentials. The main components are gravitational potential, osmotic potential and matric potential, although others such as pressure, pneumatic or overburden are in use. Gravitational potential results from the position of water relative to a selected reference elevation level, where higher the position, higher the potential. Osmotic potential reflects the effect of dissolved solutes. In case of higher concentrations, the potential is also higher, compared to a less concentrated water (Luo et al., 2022). In unsaturated soils, the matric potential is generally the principal component controlling the retention and movement of water and therefore highly relevant for soil hydrology. It results from capillary and adsorption forces in soil matrix (Kutílek & Nielsen, 1994). Soil matric potential can be used as an indicator of soil saturation, with values close to zero indicating saturated conditions (Luo et al., 2022).

Soil water potential is generally expressed in multiples of pascals (kPa, MPa) or as a pressure head given as the height of a water column (mm). Field measurements of soil water potential include several methods. One of the most common method uses tensiometers, in which soil suction is transmitted through a porous ceramic cup to the water inside the device. The resulting negative pressure is recorded. However, conventional tensiometers are generally limited to approximately -80 kPa, because or air cavitation occurring under high suction pressure (Tarantino & Mongiovi, 2001). Laboratory methods commonly combine suction and pressure based methods on soil samples. Suction methods are used when samples are close to saturation and subsequently pressure membrane apparatus are applied at lower matric potential (Kutílek, 1978).

2.4.5 Soil water availability

The soil water retention curve describes the relationship between soil water content and soil matric potential. Near saturation, most soil pores are filled with water and the matric potential approaches zero. As the soil dries, either naturally or under an applied suction or pressure, water is progressively removed from the pore space. Larger pores drain at first, followed by progressively smaller pores, because water is retained more strongly in smaller pores by capillary and adsorptive forces (Kutílek & Nielsen, 1994). The shape of the retention curve therefore reflects the pore-size distribution and is influenced by soil texture, structure, bulk density and organic matter content. Soil water retention curves are commonly described using parametric models, such as the van Genuchten model (Van Genuchten, 1980).

To classify the soil water availability a characteristic values of soil water potential (also refered as hydrolimits) and the corresponding soil moisture values are used. A fully saturated soil with a zero matric potential corresponds to the limit of full saturation. Field capacity represents the water content remaining after gravitational water drainage from large pores. It is commonly associated with pressure head of approximately -100 cm, corresponding to a matric potential of -10 kPa. This value is used as a reference of upper limit of plant available water (Kutílek, 1978).

A reduction in water availability for plants is generally observed at matric potentials around -200 kPa, where the movement of capillary water is restricted. Although the actual threshold depends on soil and vegetation properties and used classification system. Substantial water stress is conventionally defined as the permanent wilting point at the matric potential value of -1.5 MPa, corresponding to a pressure head of 150 m of water column (Kutílek, 1978).

While the permanent wilting point threshold is widely used by a soil scientists, its ecological value is less direct as different kinds of vegetation has specific water requirements. Therefore, the permanent wilting point serves as an approximation and does not generally cover all plant species (Garg et al., 2020; Torres et al., 2021). However, soil water potential is a useful metric for understanding the vegetation and water connections, complementing the soil moisture measurements.

3

Study Area

3.1 Location and site description

The study area is part of the broader Smart Landscape Amálie research initiative led by the Czech University of Life Sciences Prague. The site is located in the Central Bohemian Region, approximately 40 km west of Prague. The Amálie area lies within the Křivoklátsko Protected Landscape Area (CHKO Křivoklátsko), which is particularly valued for its extensive deciduous forests, covering approximately 62% of the protected area (AOPK, 2026).

The Amalie research site is composed of two small watersheds. The forest monitoring presented in this thesis, was conducted within the Brejlský potok catchment, which has a total area of 4.4 km^2. The stream originates partly in agricultural land and partly within the Amálie pheasantry, and subsequently flows along the forest edge through a series of small reservoirs before joining the Klíčava River.

The elevation of the study area ranges from approximately 400 to 450 m a.s.l., with gently sloping terrain and a mean slope inclination of approximately 7%.

The study area consists of three individual forested locations (denoted as 1–3), situated approximately 50–200 m apart. Each location comprises a triplet of adjacent monospecific stands of beech (Fagus sylvatica), spruce (Picea abies), and larch (Larix decidua), see Fig. 3.1.

The position of the local meteorological station, which provides reference data on precipitation and temperature obtained from an open landscape, is also indicated in (Fig. 3.1).

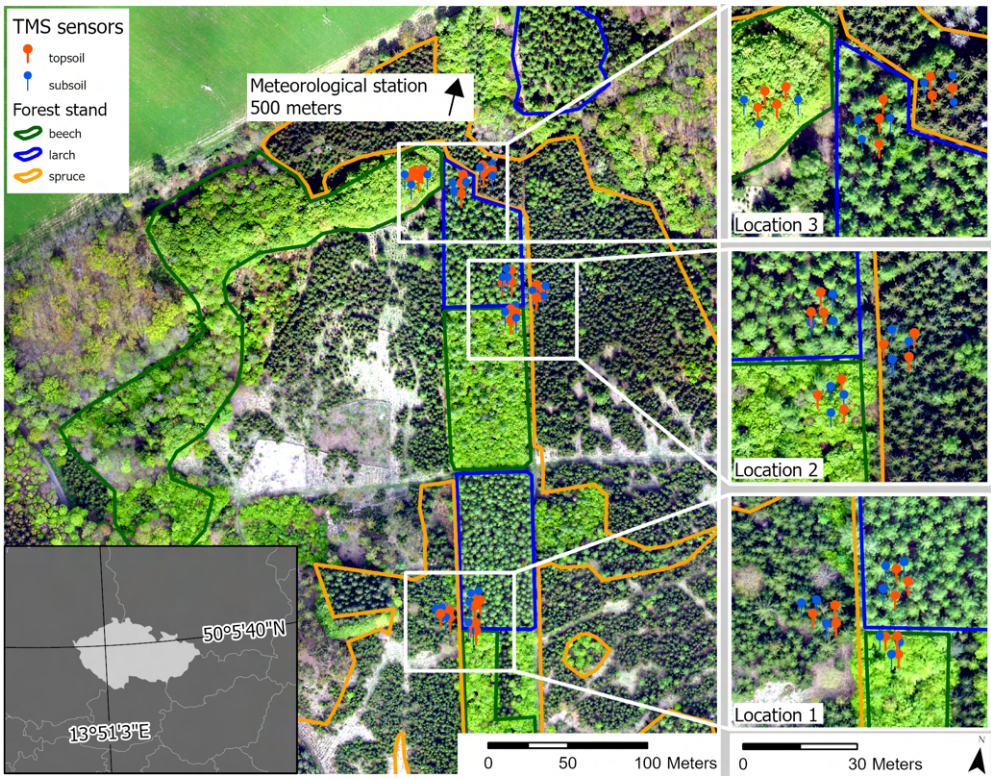


Figure 3.1: The position of individual locations, serving as a replicates for the monitoring. Adapted from Kuželková et al. (2024), produced by Ing. Jan Komárek, Ph.D.

3.2 Climate characteristics

The region is characterized by a relatively dry climate, influenced by the rain shadow effect of the Ore Mountains. The mean annual air temperature for the reference period 1991–2020 is 9.0 °C, and the mean annual precipitation is approximately 580 mm, according to the Czech Hydrometeorological Institute (CHMI). These values are consistent with locally measured meteorological data (Fig. 3.2).

The annual precipitation is close to evapotranspiration total, indicating a tight water balance. This makes the system sensitive to changes in vegetation structure and atmospheric demand.

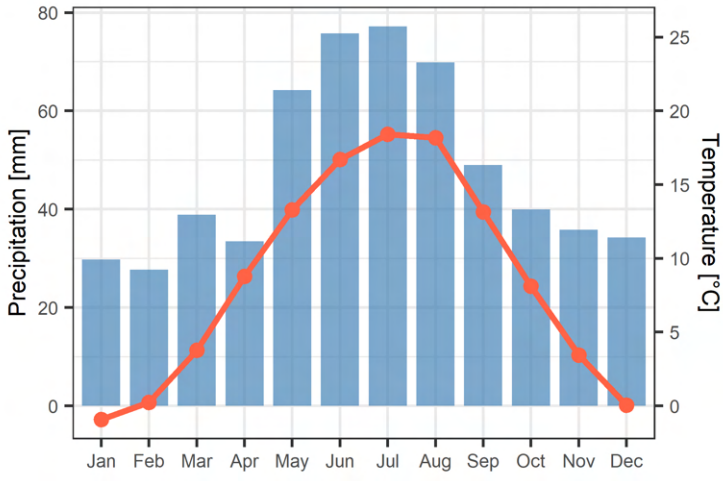


Figure 3.2: Mean monthly precipitation totals (mm, blue bars) and mean air temperature (°C, red line) in the study area.

3.3 Soil characteristics

According to the publicly available soil map dataset managed by the Czech Geological Survey (CGS), the dominant soil types in this area consists of Cambisols and Luvisols. Field surveys further refined this classification, identifying the prevailing soil type as Albic Stagnic Luvisol (Fig. 3.3).

This soil is characterized by a distinct eluvial (E) horizon with reduced clay content, overlying a Bt horizon with clay accumulation and typical reddish-brown coloration. Signs of periodic water stagnation were observed, indicating limited vertical drainage and seasonal water redistribution within the soil profile.

The organic soil layer exhibited moderate spatial variability associated with tree species composition and litter inputs. Differences in litter quality and decomposition rates resulted in distinct humus forms across the stands (Fig. 3.4), which may influence near-surface soil properties, particularly infiltration and water retention.

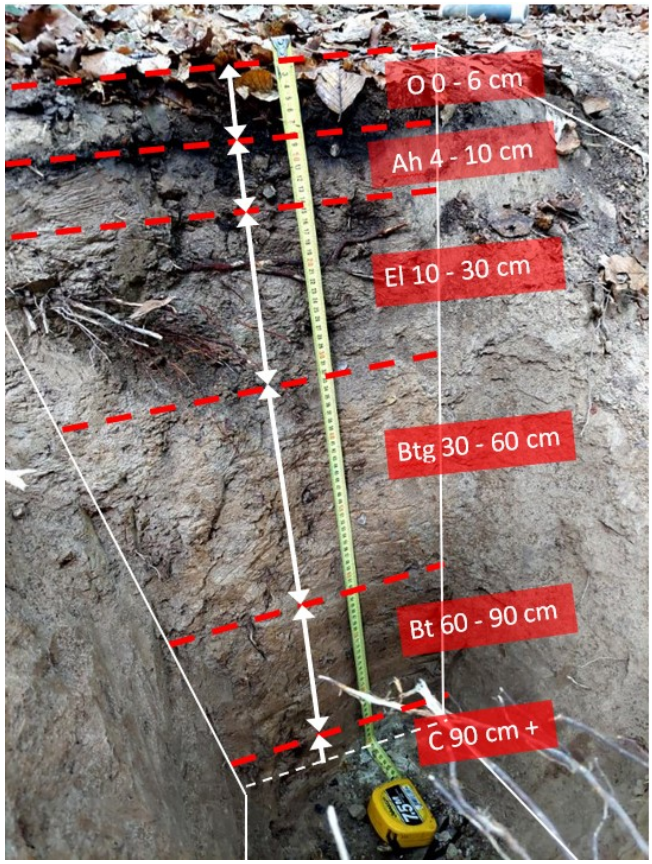


Figure 3.3: Detailed field survey identified the soil class as Albic stagnic Luvisol, characterized by eluvial horizon followed by oxidative colouration in Bt horizon. Adapted from Kuželková et al. (2024).

Figure 3.4: Representative shallow soil profiles under beech (left), larch (middle), and spruce (right) stands. The profiles illustrate differences in organic layer thickness and humus form, reflecting species-specific litter input and decomposition processes.

Mean thickness of the organic layer was 6.9 ± 2.0 cm under beech, 7.2 ±

0.9 cm under spruce, and 8.8 ± 2.0 cm under larch stands. Although these differences were relatively small, larch stands tended to exhibit slightly thicker organic layers, while spruce stands showed lower variability. These patterns likely reflect species-specific litter characteristics, decomposition processes, and soil fauna activity.

The geological substrate of the study area is formed by sedimentary shales and greywackes (Czech Geological Survey, 2026). These parent materials contribute to the development of fine-textured soils and influence the water retention and drainage characteristics of the soil profile.

Particle-size analysis confirmed a dominance of silt particles. The soil classes ranged from loam to clay loam, with silt loam as the predominant textural class. A summary of particle-size distribution across the studied stands is provided in Tab. 3.1.

Table 3.1: Particle-size distribution across tree species and soil depths. Values represent mean ± standard deviation.

Tree species	Depth	Sand [%]	Silt [%]	Clay [%]	Class
Beech	20 cm	19.00 ± 2.55	64.50 ± 2.52	16.50 ± 0.41	Silt loam
	60 cm	11.50 ± 1.29	51.50 ± 0.58	37.00 ± 0.82	Silty clay loam
	100 cm	14.25 ± 1.55	63.50 ± 0.91	22.25 ± 0.96	Silt loam
Larch	20 cm	22.38 ± 1.89	62.25 ± 1.71	15.38 ± 0.48	Silt loam
	60 cm	16.38 ± 1.80	52.75 ± 0.65	30.88 ± 1.31	Silty clay loam
	100 cm	21.50 ± 1.73	48.00 ± 1.41	30.50 ± 0.58	Clay loam
Spruce	20 cm	22.13 ± 2.78	61.63 ± 2.81	16.25 ± 0.50	Silt loam
	60 cm	21.25 ± 2.25	48.50 ± 0.71	30.25 ± 1.71	Clay loam
	100 cm	28.38 ± 2.43	49.00 ± 2.42	22.63 ± 1.65	Loam

3.4 Forest stands

The forest stands at Locations 1 and 2 are of comparable age of approximately 30 years. In contrast, Location 3 includes generally older trees, with stand ages ranging from approximately 30 to 65 years.

Tree height was estimated indirectly using drone-based measurements combined with tree counts derived from aerial imagery, and therefore represents an approximation of actual values. In contrast, diameter at breast height (DBH) was measured directly in the field for 10 representative trees per stand, followed by calculation of stand basal area. A detailed overview of stand characteristics is provided in Table 3.2.

The monitored forest stands differ visibly in canopy structure, forest-floor cover, and understory development. In beech stands the forest floor is all year round covered by leaf litter and does not show any understory vegetation. In winter, the rare snow cover is distributed evenly. The larch stands provide a

Table 3.2: Stand characteristics across the study locations. Values represent mean ± standard deviation. Adapted from Kuželková et al. (2024)

Location	Species	Age	Height [m]	N [ha^{-1}]	DBH [cm]	BA [m^2 ha^{-1}]
1	*Fagus sylvatica*	30	13.6 ± 1.0	1750	12.0 ± 5.2	23.58
	Picea abies	30	8.2 ± 1.9	850	14.9 ± 5.9	17.11
	Larix decidua	30	18.5 ± 1.4	675	22.3 ± 3.5	26.96
2	*Fagus sylvatica*	30	11.8 ± 1.1	1825	11.1 ± 2.3	18.29
	Picea abies	30	9.1 ± 1.0	900	16.7 ± 2.6	20.24
	Larix decidua	30	16.2 ± 1.4	650	22.5 ± 4.4	26.81
3	*Fagus sylvatica*	65	19.8 ± 1.4	825	25.5 ± 2.6	51.94
	Picea abies	45	13.0 ± 1.2	750	21.9 ± 5.0	29.79
	Larix decidua	30	17.1 ± 1.3	575	21.7 ± 5.1	22.36

more developed and diverse understory vegetation, presumably due to more light. In winter, snow cover on forest floor is similarly evenly distributed as in beech stands. In contrast, the snow cover under spruce appear to be thinner and with evident gaps. Otherwise the forest floor is covered by thin layer of tree litter with no apparent understory vegetation. Representative photographs of the monitored stands are provided in Appendix.

3.5 Experimental design

The experimental design was structured to capture species-specific differences in soil microclimate. Three independent locations were established as replicates, each consisting of adjacent monospecific stands of beech, spruce, and larch under comparable conditions.

The replicated design increased the robustness of the species comparison, as the observed patterns were not derived from a single location. At the same time, the locations were selected to be comparable in terms of topography, soil conditions, and local climate, as the locations are expected to have the same precipitation and temperature inputs.

Although not particularly ecologically desirable, the even age monocultural setting provided a plausible opportunity to directly compare the dynamics of soil moisture under different tree species.

The selected tree species represent dominant and functionally distinct forest types in the Czech Republic: European beech (*Fagus sylvatica*) as the location native broadleaf species, Norway spruce (*Picea abies*) as the most widespread production oriented conifer, and European larch (*Larix decidua*) as a less common but hydro-ecologically unique deciduous conifer. These species differ markedly in canopy structure, root systems and phenology, particularly in the contrast between deciduous and evergreen behaviour (Fig. 3.5), which is expected to influence precipitation partitioning and subsequently the soil water

dynamics.

Figure 3.5: The difference in canopy cover of the three species is apparent. The deciduous nature of beech and larch trees provide a pronounced seasonal effect on the precipitation partitioning and water drawing. The pictures were taken in mid April of 2024, before the new foliage development.

4

Data and Methods

This chapter describes the monitoring network establishment, data collection procedures, soil-specific calibration, and other analyses used for evaluation of tree species-specific patterns in soil moisture dynamics.

At each location, a set of TMS microclimatic stations (Wild et al., 2019) was installed and operated in a standard measurement mode with a recording interval of 15 minutes. Data were collected manually approximately twice per year, typically in early spring (March) and autumn (September). These regular field visits also allowed for systematic maintenance and quality control of the monitoring equipment.

The soil moisture dataset was further supplemented by a soil water potential measurements, collected at three mini-sites, located in selected monocultural stands of studied tree species. Each of this mini-site was equipped by four TEROS 21 (METER Group) soil water potential sensors.

To characterise site-specific soil conditions, soil samples were collected for laboratory analyses. The main soil properties were assessed through measurements of bulk density, particle-size distribution, and soil water retention curves.

Since soil moisture dynamic is closely connected to meteorological conditions, locally measured meteorological data for the monitoring period were used to complement the analyses. A context of climatic trends was further included by a 30 year long time series of monthly precipitation and temperatures, obtained by a nearby meteorological station operated by a Czech Hydrometeorological Institute.

The following sections will describe these steps in a finer detail, as much more work was needed in order to produce a reliable dataset and subsequently results of this dissertation.

4.1 Soil moisture monitoring

Soil moisture monitoring formed the core dataset of this dissertation and was designed to capture species-specific differences in soil moisture dynamic under beech, spruce, and larch trees. For the monitoring purpose a TMS stations (TOMST, Czech Republic) were selected as a robust, durable and cost-effective solution for long-term field monitoring. Each station provided measurements

of soil moisture (SM) and three levels of temperature (T1, T2, T3). However, since the vast amount of produced data, only the soil moisture dataset was used for the purpose of this dissertation.

4.1.1 TMS station installation

The base of forest monitoring was established in spring 2021 with the installation of the first set of TMS stations. A total of 54 sensors was divided equally between the topsoil and subsoil groups. The topsoil stations were used to represent the organic soil layer (SM 0-15 cm, T1 -8, T2 +2, T3 +15 cm), while the subsoil stations represented the underlying mineral soil (SM 15-30 cm, T1 -23, T2 -13, T3 +5 cm).

The topsoil stations were installed in late April 2021 by careful vertical insertion directly into the soil. Because the soil was close to saturation at the time of installation, no pre-drilling or excavation was required. Approximately two weeks later, the subsoil stations were installed. In this case, the upper part of the soil profile was carefully removed as a monolithic block, after which the stations were inserted vertically at the target depth. The excavated soil was subsequently returned in smaller portions and carefully compacted to minimise artificial preferential flow pathways around the sensor body and cable.

Table 4.1: Overview of the installed TMS4 stations according to soil layer, depth range, sensor orientation, tree species, and start of the measurenment.

Layer	Depth range (cm)	Orientation	Beech *N*	Larch *N*	Spruce *N*	Started
0–15	0–15	V	9	9	9	5/2021
15–30	15–30	V	9	9	9	5/2021
30–50	35–45, 40	D, H	6 (2, 4)	5 (2, 3)	6 (2, 4)	4/2024
50–70	60	H	4	3	4	4/2024
70–90	80	H	2	4	4	4/2024
90–115	95–115	V	3	2	4	4/2024

V = vertical orientation; H = horizontal orientation; D = diagonal orientation. Values in parentheses indicate the number of sensors installed in diagonal and horizontal orientation, respectively.

To extend the monitoring network to deeper soil horizons, additional sets of TMS stations were gradually introduced. An initial experimental extension was installed in autumn 2022. These stations were placed diagonally at intermediate depths (SM 35-45 cm; T1 -40 cm, T2 -35 cm, T3 +5 cm). This arrangement was chosen to address two methodological constraints: first, the risk of preferential flow along the cable under deep vertical installation, and second, since the soil at Amalie in deeper soil horizons is compact and dry, by a manual excavation, it is very difficult to get under the depth of 50 cm.

Figure 4.1: Metal cages are used to protect TMS stations from wildlife

In spring 2024, the monitoring network was further extended by installing an additional set of stations to capture deeper soil moisture dynamics. Because of the soil compaction, a mechanical excavator with operator was used to open a trench approximately 120 cm deep. The deeper TMS stations were installed horizontally to ensure a solid contact of soil moisture sensor and soil and to reduce the risk of preferential water flow along the cable. Owing to financial and logistical constraints, this deeper monitoring was limited to Locations 1 (tophill) and 3 (downhill). The overview of the stations counts, orientation and representative depths are provided in Tab. 4.1.

During the installation procedures, soil samples were collected for laboratory measurements.

Since the forest site is frequented by wildlife, the stations required additional protection. A scent-based repellent (Wild-Schwein-Stopp by HAGOPUR) was used initially, but its effectiveness proved insufficient due to the need for frequent reapplication and its limited protective effect. The protection was therefore replaced by metal cages (Fig. 4.1), which provided a more robust long-term solution.

4.1.2 Standardization and calibration procedures

Prior to the field installation, all of the TMS stations underwent laboratory testing and correction of the signal offset, here referred to as standardisation. The primary aim was to evaluate measurement consistency among sensors and, where necessary, adjust the raw signal used for subsequent soil moisture calculations. The signal was initially recorded across two contrasting media

Figure 4.2: Raw signal measurement of air. The values are representing the smallest possible value.

representing an extreme states of porous environment - demineralized water (maximum signal) and air (minimum signal), both at laboratory temperature (21°C) (Fig. 4.2). Later introduced TMS standardization covered as well testing standardized porous medium consisting of 2 mm glass beads under two conditions: dry and fully saturated (Fig. 4.3).

During laboratory testing, a variation in signal values between individual soil moisture sensors was detected. The resulting raw signal values were compared with the manufacturer's long-term reference values, and sensor-specific deviations from the mean were calculated. These deviations were subsequently used as correction factors for the raw monitoring signal. Findings were discussed with the manufacturer and subsequently led to improvements in the manufacturing process to ensure the best comparability between stations in future.

In order to obtain volumetric water content the raw signal values from the soil moisture sensor of TMS station has to be converted using calibration equation. A calibration equation captures the functional relationship between raw signal values and soil water content and reflect soil texture, structure and even the material properties. As manufacturer´s specifications include only mineral soil or peat, they are not very representative for forest topsoil at Amalie site. Therefore a soil-specific calibration was performed to ensure the best possible outcomes. Separate calibration soil material was collected for the upper organic-rich topsoil (0-15 cm) and the subsoil (15-30 cm) under beech, larch, and spruce stands. The soil was air-dried, cleared of coarse organic debris (e.g. leaves, twigs, bark fragments) and sieved through a 2 mm mesh to remove larger gravel particles (Fig. 4.4). The processed material was filled in stages into calibration buckets and compacted, in order to approximate the bulk density of

Figure 4.3: Obtaining raw signal values at artificial porous environment. Two left buckets are representing a fully saturated environment. Right buckets represent dry conditions. Glass beads of size 2mm were used to simulate the soil environment.

Figure 4.4: The organic and the mineral soil sampled at beech stand location 2. The soil has been cleared of large derbris (eg. twigs, leafs and gravel). Foto taken by Bc. Martin Wilczek

field conditions.

Afterwards, four randomly selected TMS4 stations were positioned into each bucket (3 per topsoil, 3 per subsoil). The buckets with stations were covered with a waterproof wrap and left to equilibrate overnight. The following day, the sensors were removed and three small soil samples from different depths were collected for each bucket to determine the mean water content by oven drying at 60°C for 48 h. The obtained gravimetric water content was converted to volumetric by using the bulk density calculated when measuring the soil volume and mass for each of the calibration buckets. The remaining soil was gradually moistened to a new target moisture level, thoroughly mixed, repacked, and measured again using the same procedure. By repeating this process, 5-7 moisture levels were obtained for each soil type, allowing the relationship between raw signal and volumetric soil moisture to be fitted.

However, subsequent field validation indicated that the absolute volumetric soil moisture values derived from the laboratory calibration in the topsoil layer required further refinement under natural soil conditions. Since its high organic content, the soil undergoes significant volume changes in laboratory conditions and therefore it can insert a bias to the calibration procedure. Therefore, an additional field-based calibration method was performed using a high-precision portable TDR probe (TRIME-PICO 64, IMKO), which was calibrated for the studied soil using undisturbed soil samples collected near the monitoring plots. This is because direct sampling at the exact position of the installed TMS4 stations could potentially disturb the sensor–soil contact, alter the local soil conditions, and promote preferential flow pathways around the stations. Therefore, a calibrated TDR probe was used as a less invasive reference method for in situ measurements in close proximity to the TMS4 stations.

These measurements were used as an indirect validation step to link the values of VWC from TDR measurenment with TMS signal values while preserving the natural hydrological conditions around the installed sensors. The calibration points were approximated by a linear relationship and used to calculate the VWC from signal values by the following relation:

$$VWC = a \cdot S + b \tag{4.1}$$

where VWC is volumetric water content, S is the raw TMS4 signal, and a and b are fitted calibration coefficients.

The calibration coefficients were specifically determined for each tree species and their values are stated in the following Table 4.2.

Table 4.2: Final calibration coefficients for the linear relationship between the raw TMS4 signal and volumetric water content.

Soil layer	Tree species	a	b
Topsoil	Beech	$2.332715760 \times 10^{-4}$	$-3.119259279 \times 10^{-1}$
	Larch	$1.920557325 \times 10^{-4}$	$-2.455281986 \times 10^{-1}$
	Spruce	$2.048711177 \times 10^{-4}$	$-2.030560194 \times 10^{-1}$
Subsoil	Beech	$2.255476007 \times 10^{-4}$	$-3.000277957 \times 10^{-1}$
	Larch	$1.749682476 \times 10^{-4}$	$-2.322482932 \times 10^{-1}$
	Spruce	$1.491736505 \times 10^{-4}$	$-1.920640816 \times 10^{-1}$

4.1.3 Preprocessing of the raw data

Data from monitoring network were collected manually in field twice a year (spring and autumn). The raw soil moisture signal values were at first corrected by a fixed sensor-specific offset of soil moisture readings obtained from a standardization procedure described in the above section. Afterwards, using the calibration equations with particular coefficients (Tab. 4.2) a signal values were converted to volumetric water content. A manufacturer calibration equation for silt-loam soil class was used to convert signal values of deeper stations as the organic content was expected to be negligible there.

Subsequently, the 15-minute records were plotted and manually inspected for error readings or other discrepancies in dataset. Periods exhibiting clear sensor malfunction (e.g. abrupt signal shifts or persistent deviations from neighbouring sensors under comparable conditions) were identified and marked as NA values. In addition, data corresponding to frozen soil conditions were excluded (T1 $<$ 0.5°C or T2 $<$ -0.5°C), as the applied calibration is not valid for frozen water and lead to abrupt shift and underestimation of signal values. After inspection and cleaning the dataset, the 15 min values were converted into daily mean aggregation for the subsequent analyses.

4.1.4 Seasonal group differences in soil moisture

Daily soil moisture values from topsoil and subsoil layers were aggregated to daily means at the level of tree species and depth group. A separate daily aggregation was performed at the level of location, tree species and depth group. This dataset was used to inspect and compare the individual locations.

To evaluate the general seasonal differences, soil moisture values were aggregated by quarters of the year. For each seasonal dataset, mean values and standard deviations were calculated. The aggregation of daily observations into seasonal summaries reduced the influence of short-term fluctuations. Normality was further evaluated using the Shapiro–Wilk test. A significance level of $p = 0.05$ was used as the threshold for statistical significance in subsequent analyses.

Seasonal differences in soil moisture means among tree species were then tested using one-way ANOVA. When significant differences were detected, Tukey's honestly significant difference (HSD) post hoc test was applied to identify which groups differed from each other. This first stage analyses was performed on the early monitoring period dataset from May 2021 to December 2022 and formed a core analysis of the published journal article "Tree trait-mediated differences in soil moisture regimes: a comparative study of beech, spruce, and larch in a drought-prone area of Central Europe" (Kuželková et al., 2024).

4.1.5 Monthly mean dynamics under years 2022 - 2025

To provide a more detailed description of the observed soil moisture dynamics of the extended monitoring period a monthly means were again calculated for the topsoil and subsoil layers. TMS stations with fewer than 15 days of valid measurements, resulting from data cleaning or occasional sensor malfunctions, were excluded to reduce potential bias caused by incomplete monthly records. The analysis was restricted to complete years from 2022 to 2025. To evaluate this extended dataset a broader approach of linear model was used. This method is analogous to repeated measures ANOVA, however is capable to cover repeated measurements, autocorrelation and difference in variance among groups, under the context of all data used in model.

At first, the analysis aimed to determine whether monthly soil moisture species-specific differences were consistent across years or varied under contrasting year-specific hydrometeorological conditions. Topsoil and subsoil layers were analysed separately because the two layers were expected to differ in their hydrological responsiveness.

Since the monthly time series exhibited substantial temporal autocorrelation, as indicated by autocorrelation function (ACF), an approach able to deal with this had to be used. A set of candidate models fitted by Generalized least squares (GLS) with a first-order autoregressive correlation structure was used to test the significance of month, year and tree species factors, where monthly mean soil moisture at the station level were used as the response variable. Temporal dependence among repeated monthly observations within each sensor was modelled using an AR(1) correlation structure by the following R notation:

```
corAR1(form = ~ time_month | ID)
```

where `time_month` represented a sequential monthly time index and `ID` identified individual sensors.

Based on previous seasonal results indicating that differences among tree species were seasonally dependent, the baseline model already included the interaction between tree species and month in addition to a simple additive effects of individual predictors. In R this is specified by short notation using $*$ symbol. A sequence of nested candidate GLS models fitted to station level

data was then used to test increasingly complex assumptions about interannual variation in species-specific seasonal soil moisture patterns:

$$M_1 : Soil\ moisture \sim tree * month + year$$

$$M_2 : Soil\ moisture \sim tree * month + month * year$$

$$M_3 : Soil\ moisture \sim tree * month + tree * year + month * year$$

$$M_4 : Soil\ moisture \sim tree * month * year$$

Nested candidate models were fitted using maximum likelihood (ML) suitable for model comparison and compared using likelihood ratio tests, and Akaike's information criterion (AIC). After model selection, the selected model was refitted using restricted maximum likelihood (REML) for final parameter estimation and residual diagnostics.

Residual diagnostics included inspection of normalized residuals against fitted values, normal quantile plots, and autocorrelation functions of normalized residuals.

Estimated marginal means were calculated for the final model to assess species-specific differences in monthly soil moisture dynamics across individual years. Pairwise post hoc contrasts were subsequently used to compare soil moisture values among tree species within individual month-year combinations. The estimated monthly marginal means were plotted, and statistically significant differences among tree species were indicated by letters.

Estimated marginal means for each month and tree species, marginalized over year, were used to represent a "typical" (mean) year for each tree species. To account for the interannual variability, standard deviations were calculated and plotted alongside the means.

4.1.6 Deeper soil layers

The raw data were preprocessed following the procedure for topsoil and subsoil sensors. A daily means of soil moisture per individual soil layers and respective tree species were calculated an plotted to visualize the daily dynamics. Further, to asses the overall soil profile evaluation in between tree species, soil water storage in the soil profile was calculated as the total sum of individual volumetric water content per soil layer multiplied by the thickness (Tab. 4.1) of the corresponding layer using following equation (Eq. 4.2):

$$SWS = \sum_{i=1}^{n} \theta_i \Delta z_i \tag{4.2}$$

where SWS is the total soil water storage in the evaluated soil profile [mm], θ_i denotes the mean volumetric soil water content of the i-th soil layer [cm^3 cm^{-3}], Δz_i represents the thickness of the corresponding soil layer [mm], and n is the number of soil layers included in the calculation.

Moreover, to directly compare the values, monthly aggregations were computed as a mean monthly soil water storage per tree and layer. Resulting values were recorded in tables by years and presented in Appendix.

4.2 Water potential

Soil water potential measurements were included as an independent complementary method to support the interpretation of species-specific differences in soil water availability. Monitoring was established at three mini-sites, one for each tree species. At each mini-site, four TEROS 21 sensors (METER Group) were installed at two depths: two sensors at 10 cm representing the topsoil and two sensors at 30 cm representing the subsoil.

The raw measurements were first aggregated to daily values for each individual sensor. Because no consistent depth-related separation was visually apparent within the monitored mini-sites, all four sensors were subsequently averaged to obtain one daily mean value per tree species. For graphical representation, soil water potential was plotted on a logarithmic scale to improve readability. Reference lines corresponding to hydrolimits thresholds to quantify water availability were added to facilitate the interpretation of vegetation water stress.

4.3 Soil properties

To describe the soil conditions in detail, a disturbed and undisturbed soil samples, collected during the station installation, were taken to laboratory. The soil textural characteristics were assessed by particle-size analyses using sedimentation methods (ISO 11277), specifically hydrometer method and later a pressure based PARIO plus (manufactured by METER Group). Samples were measured in three replicates to ensure representative values. A particle size distribution curves were constructed separately for topsoil and subsoil layers and each tree species. Further, based on the proportion of fine particles a soil class was determined and used for soil description in Chapter 3 - Study area.

Undisturbed soil samples were weighed and subsequently oven dried at 60°C for 48 hours (topsoil) and at 105°C for 24 hours (mineral soils) or until constant mass was reached. After drying, the samples were reweighed. Gravimetric soil water content was determined from the mass loss during drying and converted to reference volumetric soil water content using the corresponding bulk density.

Additional soil samples were used to determine soil water retention curves using a combination of suction and pressure based methods. However, because

the samples were collected in standard 100 cm^3 steel cylinders, the organic rich topsoil samples underwent substantial volume changes during the measurements, potentially biasing the resulting soil water retention characteristics. Therefore, the derived soil hydrolimits were used only as indicative reference thresholds for visualizing the daily soil moisture time series.

4.4 Meteorological and climate data

Meteorological data were used to provide long-term climatic context and for the interpretation of soil moisture dynamics across the monitored years. Two independent data sources were used to characterize and analyse the meteorological and climatological situation at Amálie research site. The first was in situ measurements obtained from meteorological station located approximately 300 meter away from the location 3 in open field. This dataset produced daily sums of precipitation relevant used to complement the daily soil moisture data.

Second dataset, is represented by long-term time-series of precipitation and air temperature adapted from CHMI (Czech hydrometeorological institute, in Czech abbreviated as ČHMÚ), collected at a meteorological station in Lány village, located approximately 7 km from the Amálie research site. This dataset was used to asses a monthly mean temperature and monthly precipitation sums anomalies from a long-term normals calculated for the values of past 30 years (1991 - 2020). Further, air temperature data were used to calculate a cumulative growing degree day (GDD) with a base temperature threshold of 5°C. Calculations were based on following equations (Eq. 4.3, 4.4):

$$GDD_{\text{day}} = \max\left(0, T_{\text{mean}} - T_{\text{base}}\right) \tag{4.3}$$

$$GDD_{\text{cum}} = \sum_{i=1}^{n} GDD_{\text{day},i} \tag{4.4}$$

where GDD_{day} represents the daily growing degree day value, GDD_{cum} represents the cumulative growing degree day value, T_{mean} is the mean daily air temperature, T_{base} is the base temperature below which vegetation growth is assumed to be negligible, n is the number of days since the beginning of the accumulation period, and i is the index of a given day.

4.5 Data processing and software

Data preprocessing and manipulation, statistical analyses, and graphical outputs were primarily carried out in the R programming language using the RStudio environment version 2025.09.2 (R core Team, 2025). Microsoft Excel was partially used as a supporting tool for initial data inspection, manual checking, and organization of selected small datasets and metadata.

5

Results

This chapter first provides an overview of the meteorological conditions during the monitoring period, followed by a description of the observed soil moisture patterns based on daily values from the topsoil and subsoil layers over the entire study period. Seasonal and monthly mean soil moisture patterns are then evaluated, and periods with statistically significant differences among the studied tree species are identified. Subsequently, data from the extended monitoring network are used to assess soil moisture dynamics in deeper soil layers and total soil water storage within the soil profile to a depth of 115 cm. Finally, soil water potential data are presented as an independent method complementing the observed soil moisture patterns.

5.1 Meteorological and climatic context

The analysed period (2021–2026) exhibited substantial inter-annual variability in both temperature and precipitation regimes. The year 2021 was characterised by pronounced negative temperature anomalies in late spring (April–May), followed by moderately warm conditions in June (Fig. 5.2). Precipitation was above normal during late spring and early summer, suggesting favourable conditions for soil water recharge, although a subtle precipitation deficit in early autumn occurred (Fig. 5.3). The year 2022 showed predominantly positive temperature anomalies, with a short colder episode in April. Precipitation was heterogeneous, alternating between deficit and surplus conditions across the year. The following year, 2023, was markedly warm, with persistent positive temperature anomalies throughout most of the year, interrupted only by a brief spring frost episode caused mainly by near zero temperatures in first week of April. Following months were further characterised by a significant precipitation deficit particularly in summer. This was partially compensated by the above normal precipitation at the end of year.

The year 2024 represented the most extreme conditions within the analysed period, with unusually high temperature anomalies. Apart from November, all of the monthly mean temperatures were above long-term normal. Exceptionally high temperatures were detected in February (+5.5°C) and March (+ 3.2°C). Precipitation was moderately uneven, with a subtle precipitation deficit until September, when a pronounced precipitation event passed across Czechia during

the period of 13 - 16th. November. In total accounting for 105.4 mm at Lány station. In contrast, 2025 exhibited relatively stable conditions, with only minor deviations from long-term averages in both temperature and precipitation. Slightly drier conditions prevailed for most of the year, although a localized precipitation surplus was observed in November. Finally, the incomplete record for 2026 suggests a drier onset of the year, based on the available early-season data.

The individual years 2022, 2023, and 2024 were overall substantially warmer (Tab. 5.1). The annual amount of precipitation was generally close to the long-term normal, with the exception of the year 2021, where the yearly total amount reached to 656 mm and slightly under normal years 2023 (545 mm) and 2025 (518 mm). However, it should be noted that the otherwise significantly dry year 2024 was substantially enhanced by the dominant precipitation event in September.

Table 5.1: Annual summary of precipitation and air temperatures compared to the long-term normal.

Year	2021	2022	2023	2024	2025	2026	Normal
Temperature [°C]	8.3	9.6	10.1	10.3	8.8	–	8.6
Precipitation [mm]	656	559	545	607	518	–	559

To place the monitoring period within the broader context of recent climatic trends at the Amálie site, cumulative annual growing degree days (GDD) were evaluated for the period 1995–2025 (Fig. 5.1).Thermal accumulation remained limited during winter and showed relatively little variation among years. From approximately day 100, cumulative GDD increased rapidly with the onset of spring, and differences among individual years progressively developed throughout spring and summer. By approximately day 300, the curves generally approached a plateau as thermal accumulation declined toward the end of the year. Final annual GDD totals ranged from approximately 1,700 to 2,500 °C, with the highest values occurring predominantly during the last decade. This pattern indicates a substantial increase in thermal accumulation over the evaluated period. The year 2024 was particularly exceptional, deviating markedly from the typical pattern from early spring and subsequently resulting as the second highest annual GDD within the analysed period.

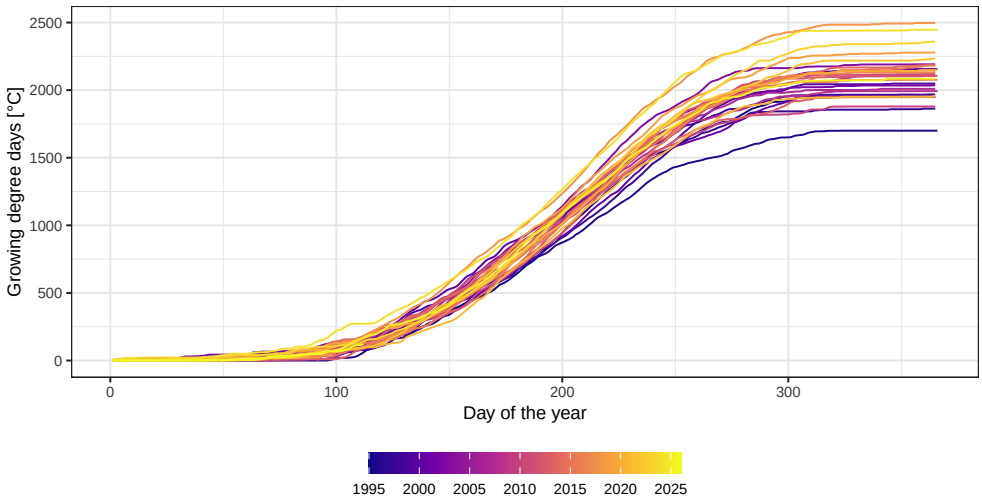


Figure 5.1: Growing degree days across the period 1995 - 2025. A cumulative sum of daily temperatures above the threshold of 5°C illustrates the shift in annual heat accumulation over the past 30 years.

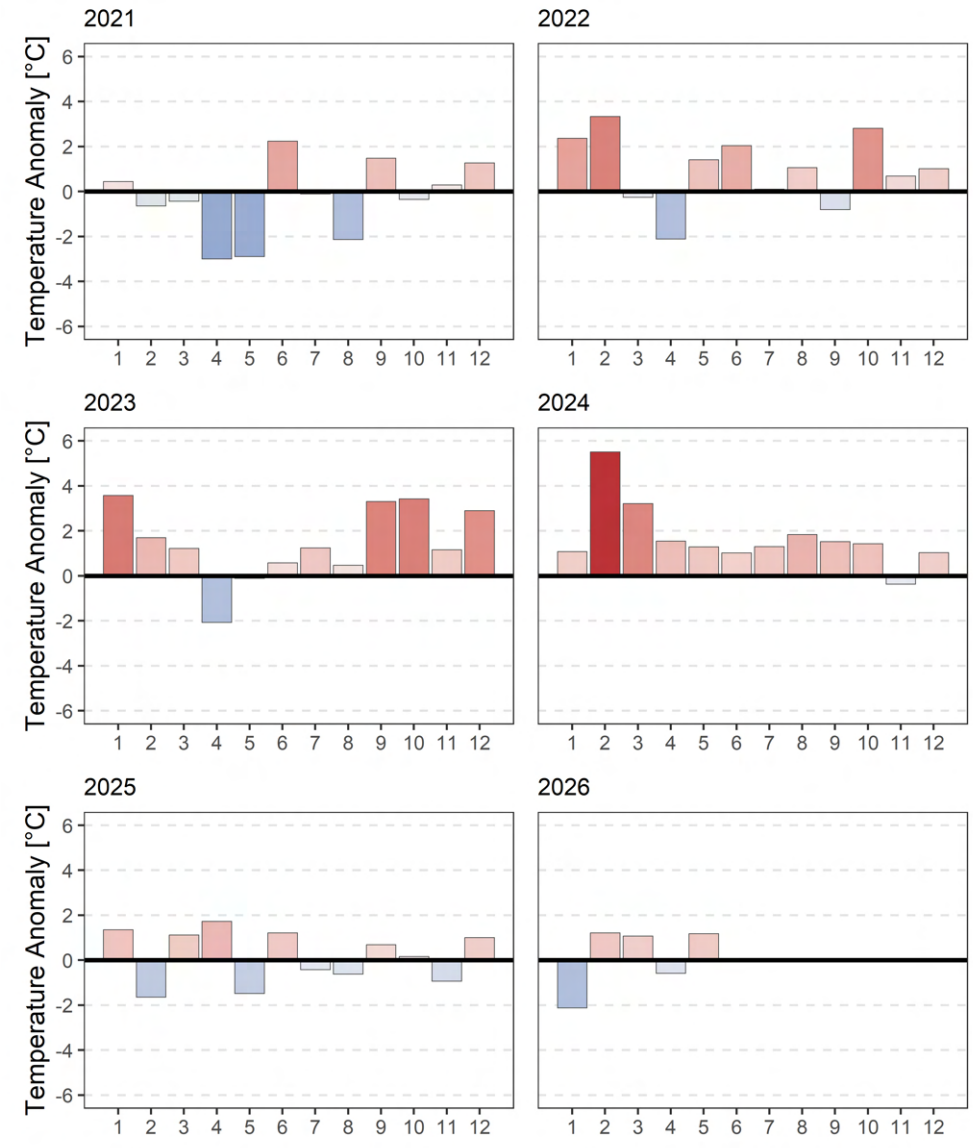


Figure 5.2: Monthly air temperature anomalies relative to the long-term normal (1991-2020) at the Lány station for the period 2021–2026.

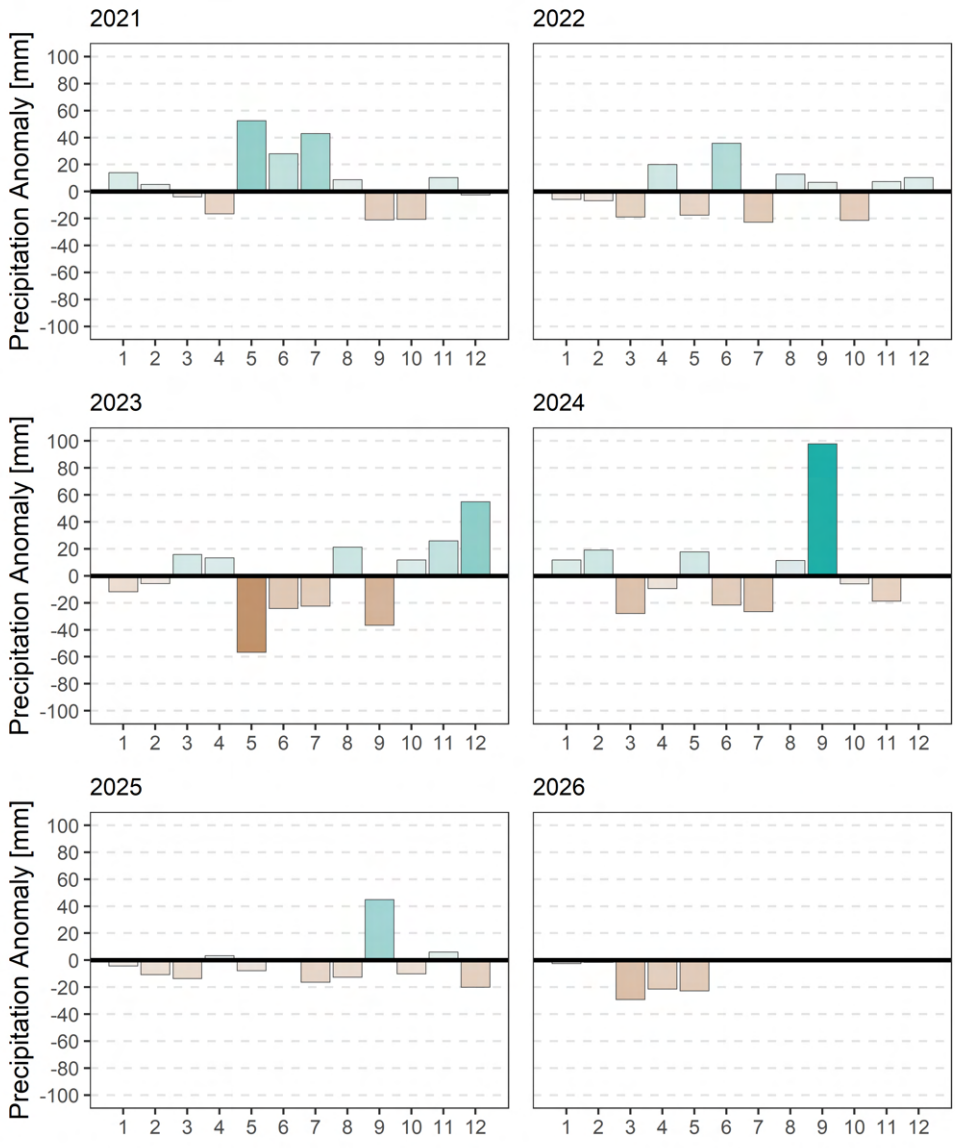


Figure 5.3: Monthly precipitation anomalies relative to the long-term normal (1991-2020) at the Lány station for the period 2021–2026.

5.2 Soil moisture dynamics

This section presents the results covering the shallow topsoil and subsoil layers over the period 2021–2026. As the longest and most spatially extensive dataset, it provides the primary basis for evaluating the patterns of soil moisture dynamics and differences among the studied tree species.

5.2.1 Seasonal patterns of soil moisture

The seasonal course of soil moisture showed a consistent pattern, repeating across the monitored years (Fig. 5.4). The winter period was characterised by a recharge phase, followed by a progressive depletion during spring, leading to minimum soil moisture values in summer. Subsequently, a gradual recovery occurred during autumn. This general pattern was observed across all years and tree species. However, interannual variation and differences in the timing of soil depletion across different tree species were observed.

Short-term fluctuations in soil moisture closely followed daily precipitation inputs, with distinct peaks associated with individual rainfall events. These responses were more pronounced in the topsoil layer and became progressively attenuated with increasing depth. Consequently, soil moisture variability was substantially higher in the topsoil compared to the subsoil.

Individual tree species exhibited distinct soil moisture regimes, reflected in repeating differences in moisture levels. Beech and larch showed similar dynamics during the spring depletion phase, characterised by a pronounced decrease in soil moisture typically occurring in early May. In contrast, spruce exhibited an earlier onset of soil moisture depletion compared to the deciduous species, indicating a earlier start of its vegetation season. An exception was observed in 2024, when the onset of soil moisture decline under larch occurred up to two months earlier than in beech, following the decrease of spruce. This anomaly was consistent across both topsoil and subsoil layers. A similar situation was observed in early spring 2026. However, since the data evaluation period ended during the spring, the full seasonal development could not be properly captured.

Across the study period, during the spring season, beech soil consistently maintained the highest soil moisture levels. In contrast, spruce exhibited the lowest soil moisture during this period. However, in late summer, soil moisture levels across all species converged to similar values prior to the onset of autumn recharge. Under peak summer conditions, larch in the topsoil horizon temporarily exhibited lower soil moisture levels than spruce stands.

Variability among individual locations was in general small, with species-specific patterns dominating the observed dynamics. These results are presented in appendix. A minor difference was observed in topsoil layer of the spruce stand, where soil moisture levels at Location 2 were consistently higher than Location 1 and 3 (Fig. A.7). On the other hand, those two locations showed surprisingly

similar temporal dynamics, which possibly emphasized the difference with Location 2. The soil moisture levels at individual locations were in general more similar in the subsoil layer (Fig. A.8) with no systematic deviation in between locations with respect to tree species.

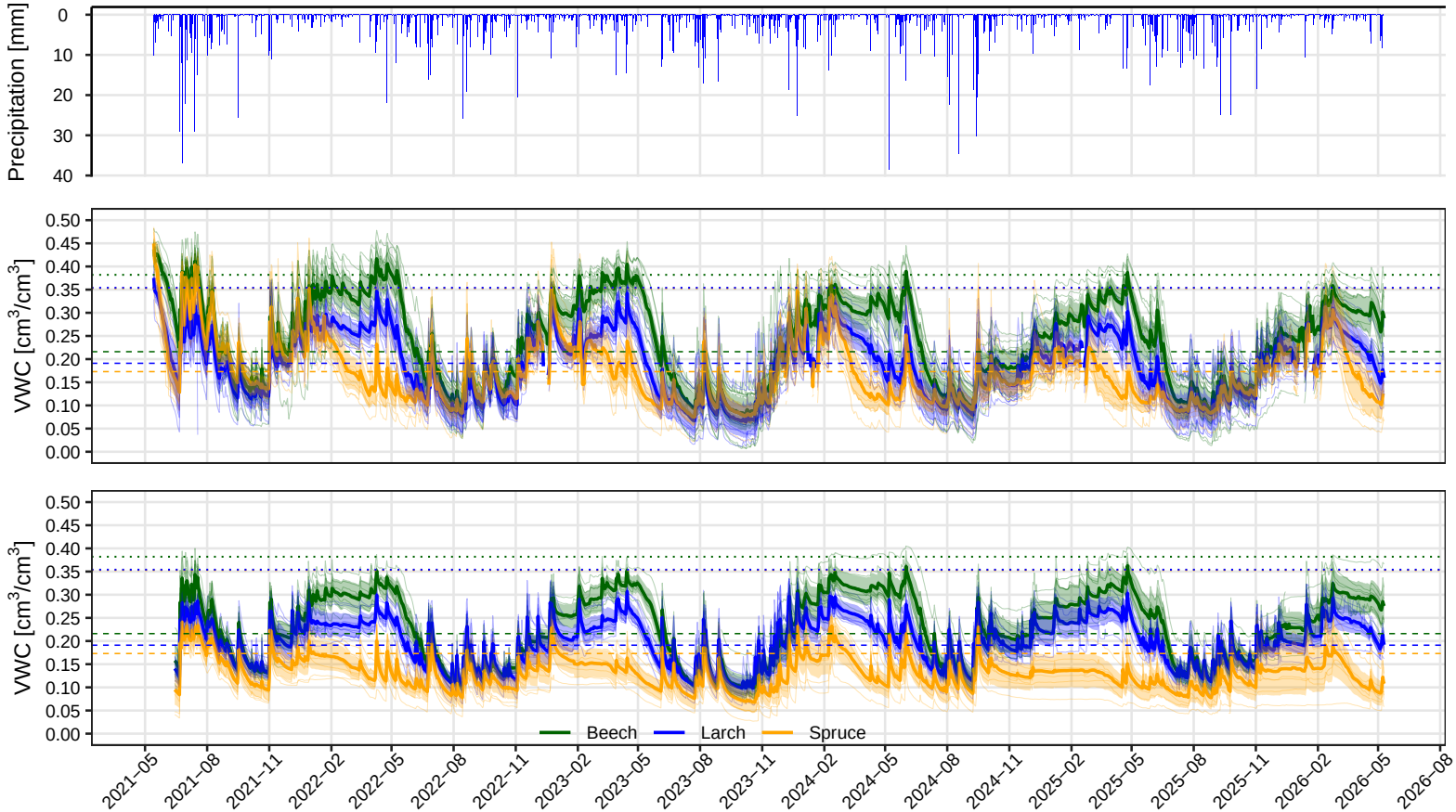


Figure 5.4: Soil moisture dynamics in the topsoil and subsoil layers together with daily precipitation. A thick line represent mean values for topsoil(middle panel) and subsoil(bottom panel) and thin lines represent a daily values from individual sensors. Green colour is used to identify the beech forest, blue for larch forest and orange for spruce stands.

5.2.2 Tree trait mediated differences

These results formed the core for published journal article - Tree trait mediated differences: A comparative study of beech, larch and spruce trees in a drought-prone area of Central Europe (Kuželková, 2024) and therefore were intentionally kept in its original published form, covering for an early evaluation period (May 2021 to December 2022).

The results of seasonal aggregation showed statistically significant differences in mean soil moisture values across the tree species. In both layers, the highest values were generally observed during first two quarters of year (Jan–Mar, Apr–Jun), while the lowest values occurred during the summer period (Jul–Sep 2022). Autumn (Oct–Dec) was characterized by an increasing recovery of soil moisture. Across most periods, beech stands showed the highest soil water content, while spruce exhibited the lowest values, and larch displayed intermediate behaviour. The differences among species were more pronounced in the topsoil, whereas in the subsoil they were reduced and more variable.

Statistically significant differences between tree species were detected in most periods, with the exception of Jul-Sep 2022, where no significant differences in between tree species means were detected. For topsoil (Fig. 5.5), beech frequently formed a separate group with higher soil moisture, while spruce was often significantly lower. In several periods (e.g., Jul–Sep 2021, Oct–Dec 2022), larch did not differ significantly from spruce, but remained significantly lower than beech. Significant differences in topsoil for all three tree species occurred in Apr-Jun period of 2022.

In the subsoil (Fig. 5.6), significant differences in between all tree species occurred in the Jan-March 2022 period and following Apr-June 2022. All periods showed statistically significant differences between groups of beech and spruce trees, while beech-larch differences were significant from Jul-Sep 2021 to Apr-Jun 2022. The larch-spruce differences were observed in all periods with exception of period Jul-Sep 2021.

The results indicated consistent species-specific differences in soil moisture, with the most pronounced differences occurring in first half of the year. These differences tend to be less pronounced with soil depth and to decrease during summer months.

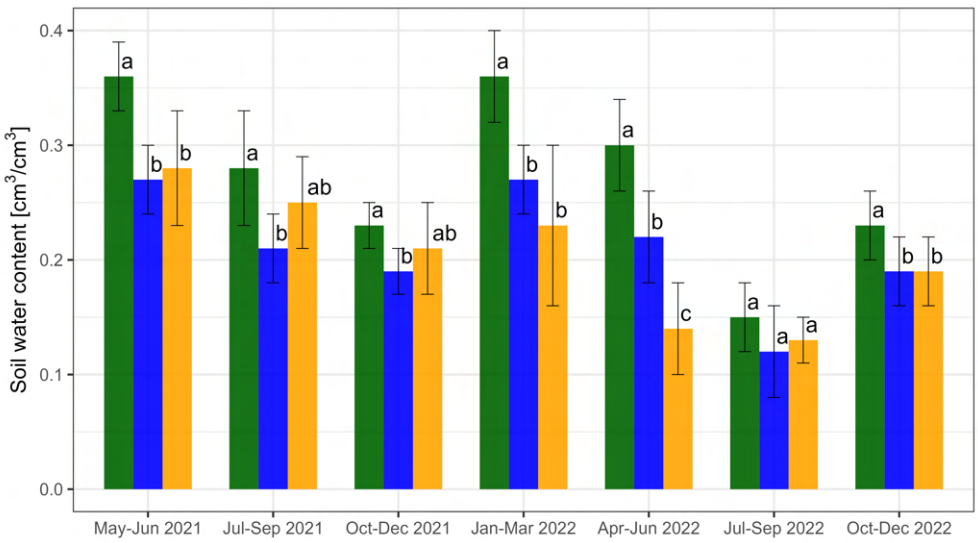


Figure 5.5: Topsoil mean soil moisture seasonal differences in between tree species. Statistically significant differences are denoted with individual letters (a, b, c). Colours represent individual tree species, green - beech, blue - larch, orange - spruce.

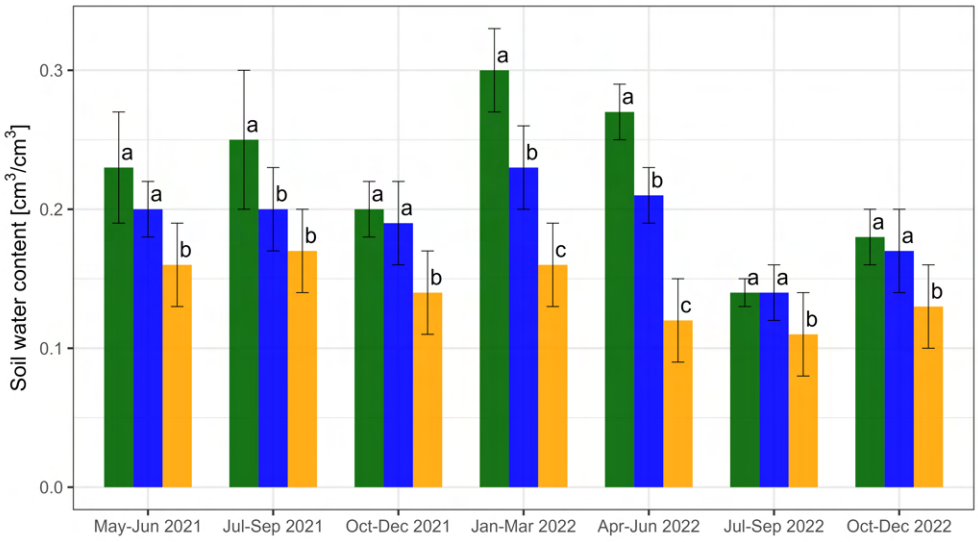


Figure 5.6: Subsoil mean seasonal differences in between tree species. Statistically significant differences are denoted with individual letters (a, b, c). Colours represent individual tree species, green - beech, blue - larch, orange - spruce.

5.2.3 Mean monthly species-specific differences

Nested GLS model comparison showed that monthly soil moisture dynamics were strongly structured by tree species, month, and year in both topsoil

and subsoil (Tab. 5.2). In both layers, the full model including the three-way interaction of tree species × month × year, significantly improved the fit compared with the other candidate models. The full models also had the lowest AIC in both, topsoil (AIC = -6739.71) and subsoil (AIC = -6522.07) among tested models. These results indicate that species-specific seasonal soil moisture patterns were not stable across years, but varied among specific month-year combinations in both soil layers.

The final topsoil and subsoil models were refitted using the REML for further analyses. The estimated AR(1) coefficient was high in both layers, with $\phi = 0.916$ for topsoil and $\phi = 0.943$ for subsoil, indicating strong temporal dependence among repeated monthly observations within sensors. The ANOVA on final model confirmed the significant three-way interaction in both soil layers (topsoil: $F = 3.97$, $p < 0.0001$; subsoil: $F = 3.36$, $p < 0.0001$).

Table 5.2: Comparison of nested GLS models for monthly soil moisture in topsoil and subsoil. Models were fitted using maximum likelihood.

Layer	Comparison	Added structure	χ^2	Δdf	p
Topsoil	M1 vs. M2	month × year	1058.19	33	< 0.0001
Topsoil	M2 vs. M3	tree × year	4.37	6	0.6267
Topsoil	M3 vs. M4	tree × month × year	263.23	66	< 0.0001
Subsoil	M1 vs. M2	month × year	1077.21	33	< 0.0001
Subsoil	M2 vs. M3	tree × year	13.35	6	0.0378
Subsoil	M3 vs. M4	tree × month × year	228.19	66	< 0.0001

Residual diagnostics indicated acceptable model fit for both layers. Normalized residuals were approximately normally distributed in the central part of the distribution, although moderate deviations occurred in the tails. The ACF of normalized residuals showed that the AR(1) structure substantially reduced short-lag temporal autocorrelation, with only weak residual autocorrelation remaining around seasonal lags.

Post hoc comparisons of estimated marginal means were used to identify the significant differences in between tree species within each month and year. In the topsoil layer (Fig. 5.7), monthly soil moisture differed significantly among tree species mainly during the first half of the year. Across all analysed years, beech generally showed the highest monthly soil moisture. For the topsoil layer, statistically significant differences between beech and spruce were consistently observed from January to June. In January and February, spruce and larch generally did not differ significantly from each other, however both were significantly drier than beech. From March to May, monthly soil moisture values were usually significantly different among all three tree species, with beech showing the highest values, larch intermediate values, and spruce the lowest values.

From July onwards, monthly soil moisture largely converged and no statisti-

cally significant differences among tree species were detected, with the exception of beech in November 2022 and December 2024. This convergence indicates that during the driest part of the year, topsoil moisture became comparable under all tree species. This seasonal pattern was repeated across years, although the magnitude and timing of the differences varied among individual years, as also supported by the significant three-way interaction in model specification. The year 2024 showed a slightly different pattern, with an earlier convergence between larch and spruce.

In the subsoil layer (Fig. 5.8), the first half of the year showed statistically significant differences in between all species, with the exception in the beginning of 2025. In the second half of the year, soil moisture under beech and larch generally became similar and, with a few exceptions, did not differ significantly. However, the differences between spruce and the other two tree species remained evident during most of the monitored period and most of the time statistically significant. This suggests that, compared with the topsoil, the species-specific differences were more persistent in the subsoil, mainly due to consistently lower soil moisture under spruce.

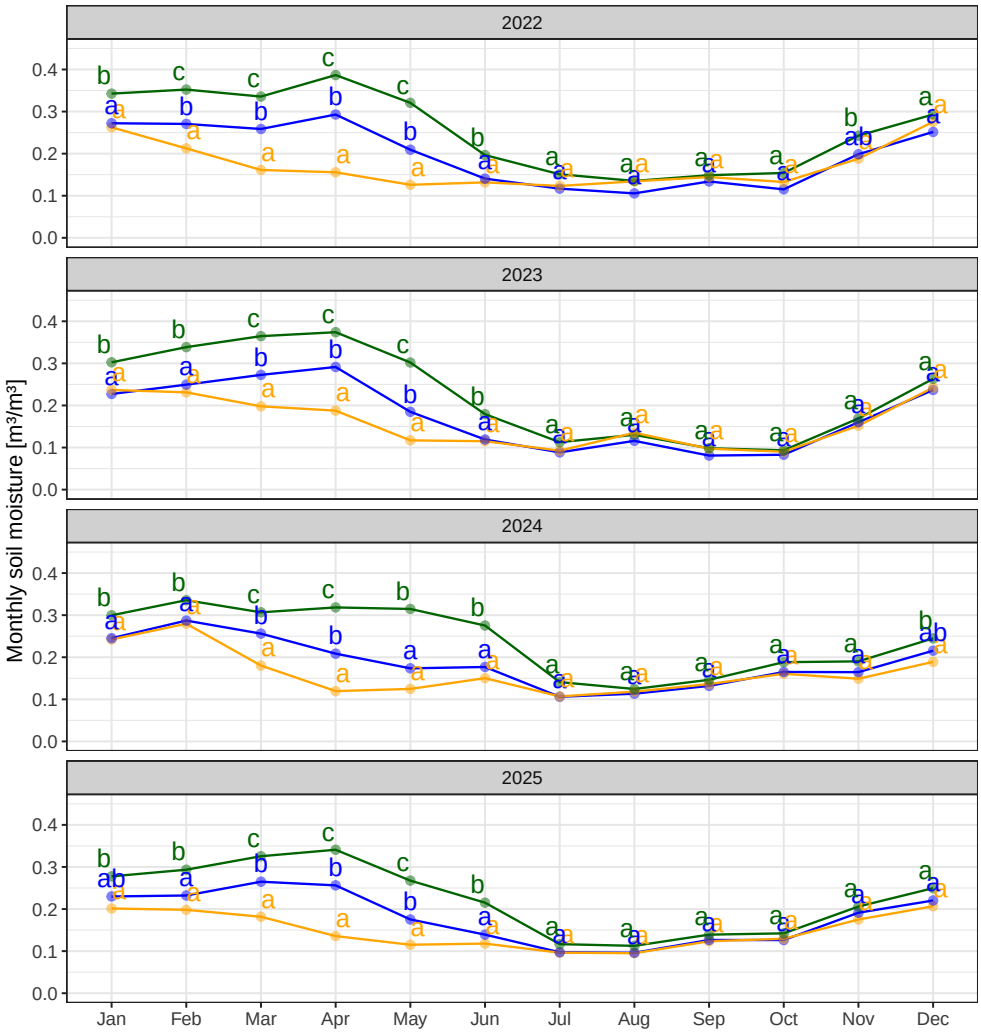


Figure 5.7: Monthly soil moisture dynamics in the topsoil layer (0–15 cm) under beech, larch, and spruce stands from 2022 to 2025. Points and lines represent model-estimated monthly mean soil moisture derived from the GLS model. Lowercase letters indicate a statistically significant differences.

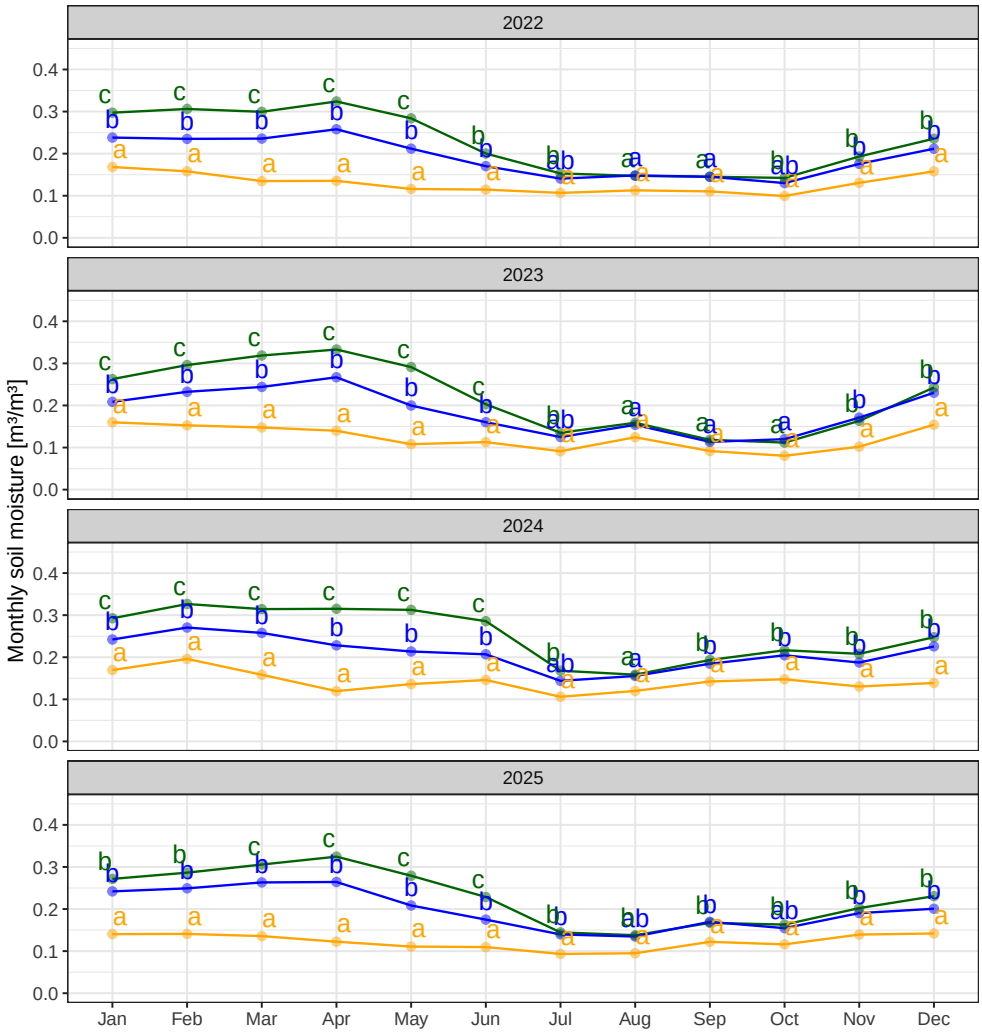


Figure 5.8: Monthly soil moisture dynamics in the subsoil layer (15–30 cm) under beech, larch, and spruce stands from 2022 to 2025. Points and lines represent model-estimated monthly mean soil moisture derived from the GLS model. Lowercase letters indicate a statistically significant differences.

The estimated mean year showed that in some months, a considerable variability across years was observed. In general, the standard deviations in topsoil (Fig. 5.9) were higher than in subsoil (Fig. 5.10). The highest variability was observed in April across all tree species, which reflect the differences in timing of the soil moisture depletion onset among years. In beech stands, higher variability was also observed in June. During summer, variability among individual years was low for all tree species in both the topsoil and subsoil. In the rest of the year, variability was generally more pronounced in the topsoil, although the subsoil showed comparable variability in September and October. This suggests that the largest differences occurred mainly during seasonal transition periods in spring and autumn.

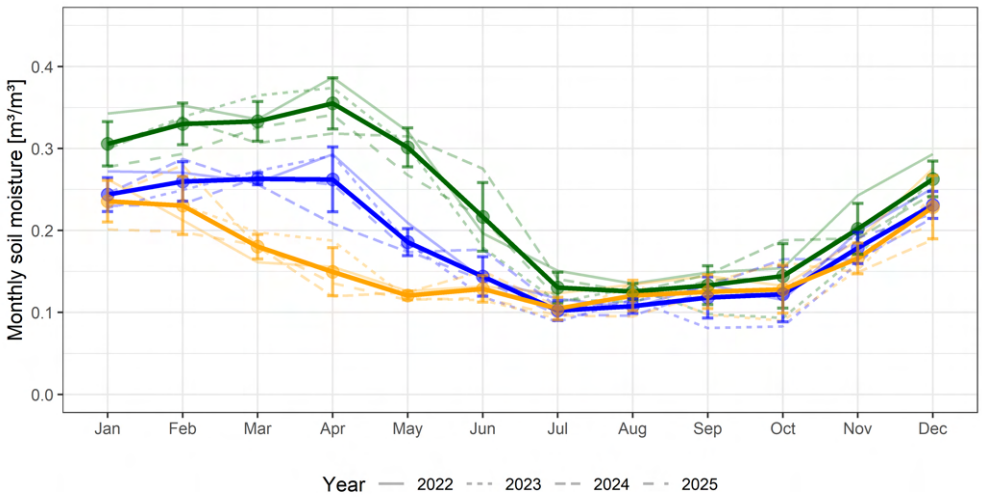


Figure 5.9: Mean annual pattern of monthly soil moisture in the topsoil layer (0–15 cm) under beech, larch, and spruce stands. Thin lines represent estimated monthly means for individual years, while thick lines and points show the mean monthly pattern across years. Error bars indicate interannual variability expressed as standard deviation.

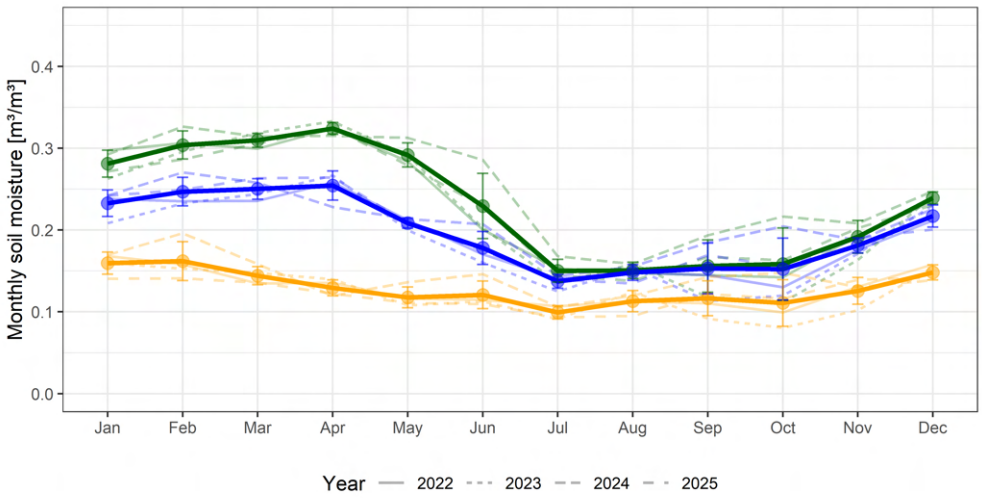


Figure 5.10: Mean annual pattern of monthly soil moisture in the subsoil layer (15–30 cm) under beech, larch, and spruce stands. Thin lines represent estimated monthly means for individual years, while thick lines and points show the mean monthly pattern across years. Error bars indicate interannual variability expressed as standard deviation.

5.3 Vertical soil moisture distribution and water storage

Deeper soil layers monitoring was included to assess the vertical distribution of soil moisture and its variation in between tree species accounting for different rooting zones of studied trees.

5.3.1 Depth-dependent soil moisture patterns

Across all tree species, soil moisture exhibited a depth-dependent pattern, with higher volumetric water content consistently observed in deeper soil layers (Fig. 5.11). The upper soil horizons showed substantially greater temporal variability, responding rapidly to precipitation inputs and subsequent drying. This pattern reflects the damping effect of depth, where short-term fluctuations are progressively attenuated with increasing soil depth.

Differences among tree species were observed in the vertical coupling between soil layers. Beech stands showed relatively strong coupling, with similar temporal dynamics across depths, indicating a coherent response of the soil profile. In contrast, spruce stands exhibited distinct separation of shallow (topsoil and subsoil) and deeper layers. Larch stands displayed seasonal dynamics comparable to beech, with soil moisture in deeper layers remaining stable or slightly increasing during the winter recharge period. In contrast, under spruce, soil moisture in deeper horizons showed a gradual decline already after peak

in mid September 2025, associated with an extreme precipitation event as described in section 5.1.1.

A cross sectional visualization of soil moisture profiles over time (Fig. 5.12), showed a distinctly drier shallow soil layers in spruce stands throughout the monitoring period, with generally only a short-term increase following precipitation events. In contrast, under beech and larch, shallow soil layers showed significant recharge during the winter and spring periods.

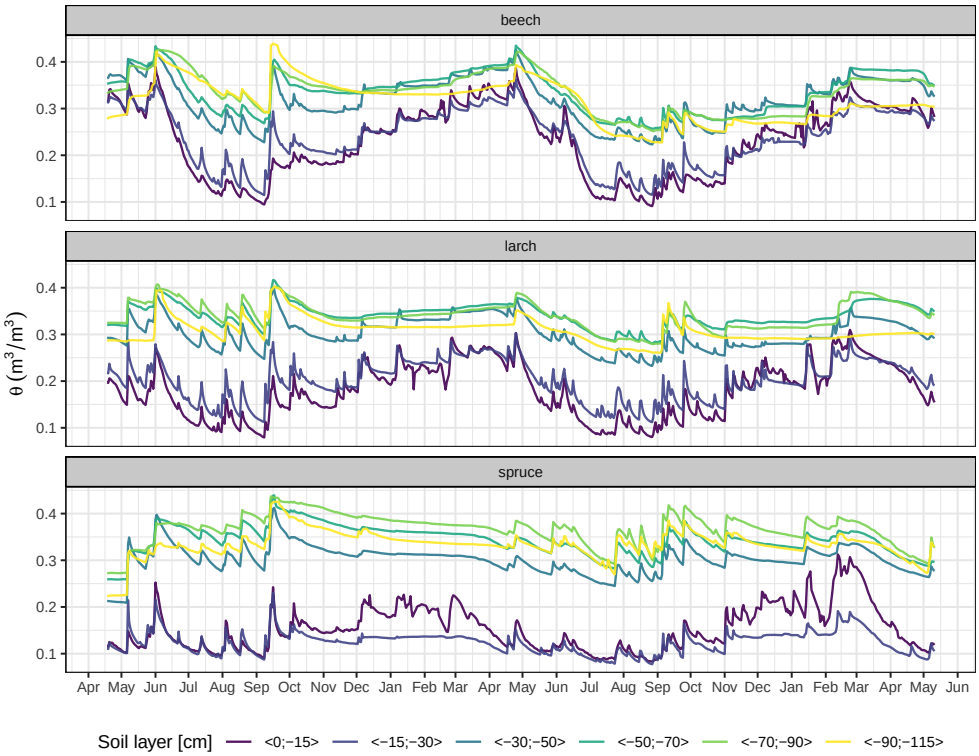


Figure 5.11: Seasonal dynamics of soil moisture for individual soil layers under beech, larch, and spruce stands during 2023–2025. Lines represent mean values for each depth interval. Shallow layers show high temporal variability, while deeper layers exhibit damped responses.

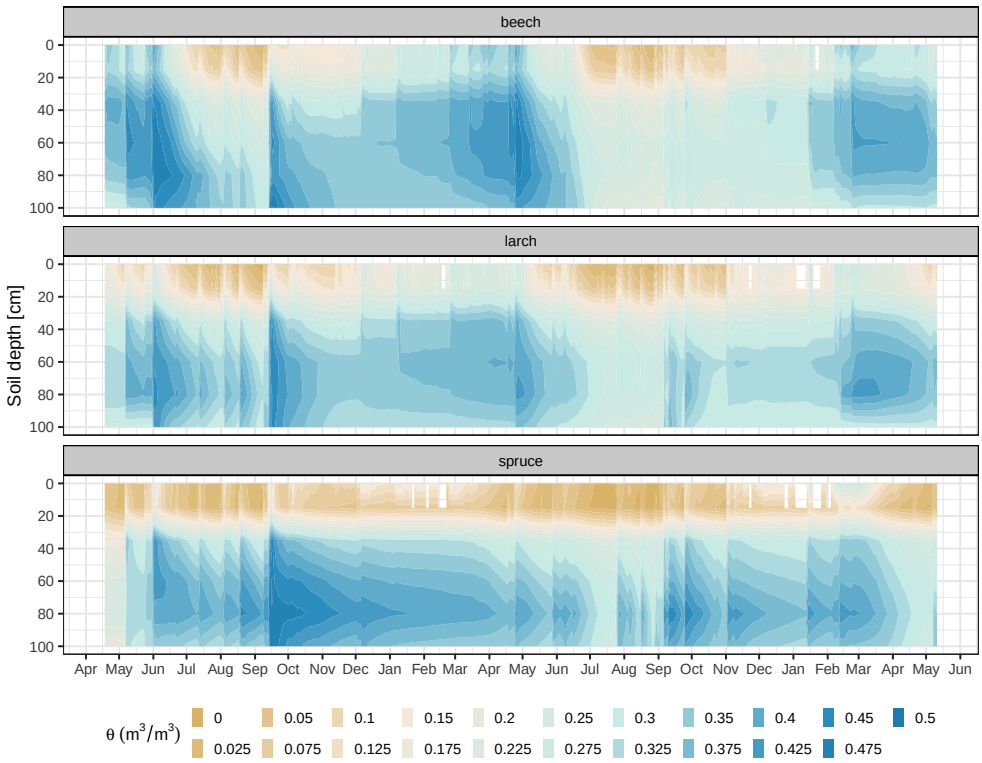


Figure 5.12: Cross-sectional visualization of volumetric soil moisture under beech, larch, and spruce stands during 2024–2025. Colours represent soil moisture values across the profiles (0–115 cm). The figure highlights seasonal recharge and depletion patterns and the vertical propagation of moisture, with reduced downward connectivity under spruce compared to beech and larch.

5.3.2 Soil water storage across the profiles

The mean monthly water storage across individual profiles exhibited strong seasonal patterns. Over the first six months, the mean monthly water storage was highest in beech and lowest in spruce, with larch in the middle. However, the other half of the year reversed the pattern with spruce having the highest total soil water storage across the soil profile and beech the lowest (5.13). Generally, the lowest values were observed in summer months, across all tree species with an exception of spruce, that in the year 2024 exhibited a global minimum already in May. The lowest value for larch in this year appeared in July and one month later in beech. The following year 2025 showed similar pattern, with a minimum for spruce in July and in August for larch and beech. The values of August 2025 represented both global year minimum and overall global minimum of soil water storage at the level of 251 mm in beech. Interestingly, the year 2025 also produced an overall global maximum in beech forest in April at the level of 428 mm. Therefore, over the course of four months, the water

storage in beech decreased by 177 mm (41%). Although spruce generally tend to early but relatively moderate decrease, in spring months of 2026 a steep decrease in overall water storage under spruce was observed. By the end of the dataset, in April, the spruce (291 mm) was already nearly at the level of its global minima observed in July of 2025 (281 mm). This suggests a serious water deficit in soil profile. The tables containing the average monthly values for separate layers grouped by tree species are provided in Appendix. The daily values of soil water storage, contributed by separate soil layers are showed in Fig. 5.14.

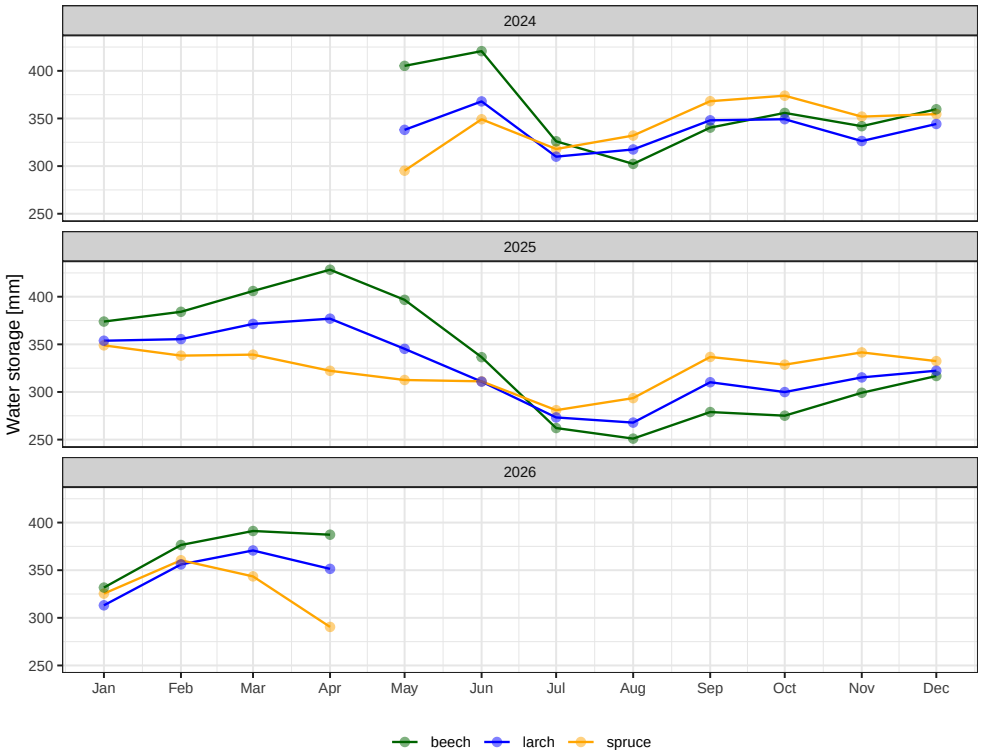


Figure 5.13: Monthly sums of total water storage across the soil profile grouped by tree species.

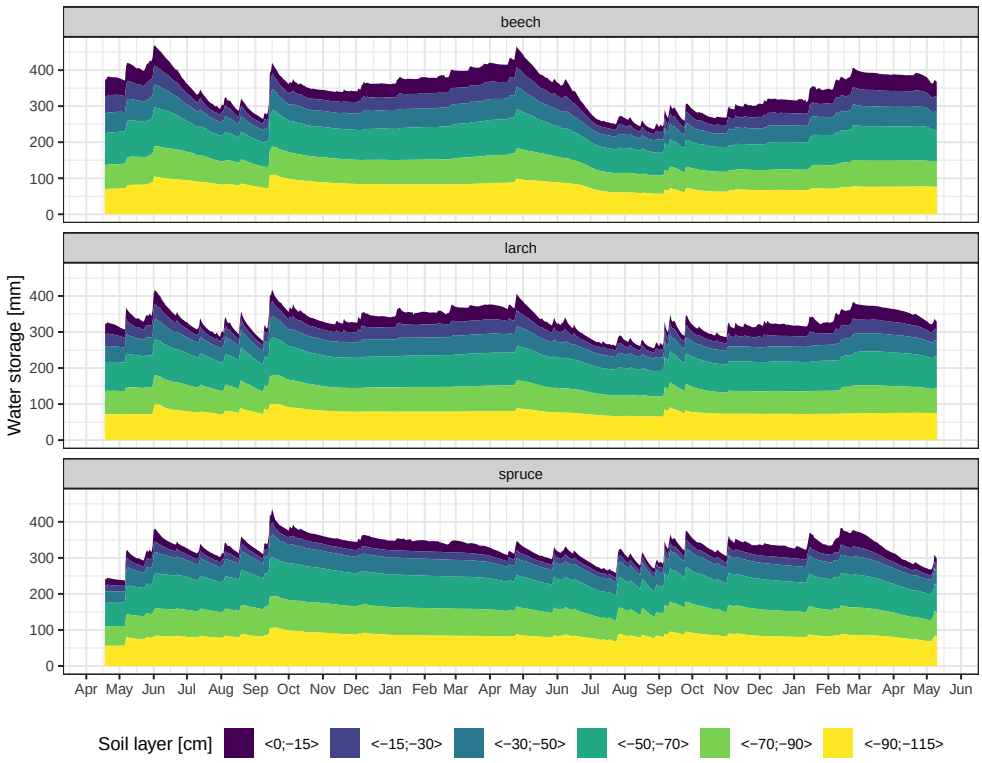


Figure 5.14: Dynamics of soil water storage (mm) in individual layers across the 0–115 cm soil profile under beech, larch, and spruce stands during 2023–2025. Colours indicate the contributions of individual soil layers to total soil water storage.

5.4 Soil water potential

Soil water potential showed pronounced species-specific differences in soil water recharge and depletion patterns (Fig. 5.15). Across all monitored years, soil water potential exhibited clear seasonal cycle, with rapid decline during the vegetation period and recovery during autumn and winter, consistent with the soil moisture observations. An early-spring decrease in spruce forest was evident across all years. Most of the years (2024, 2025, 2026) showed a decrease in spruce stand starting in March, with an exception of 2023, where less pronounced but arguably earlier decrease was observed. During peak summer periods, soil water potential converged across all tree species, reaching values close to the wilting point (approximately -1500 kPa), suggesting substantial water limitations for all tree species.

The larch and beech stands were relatively consistent in the timing of soil water potential decrease, following a distinct shift of approximately two weeks in between larch and beech soil water depletion. The exception is 2024, where, consistent with the soil moisture observations, the soil water depletion in larch

trees started significantly earlier, during March, however was later successfully replenished by significant precipitation of 38 mm on May 7. This replenishment was only partial in spruce forest.

Similar situation repeated later in September where over the span of 4 days an extreme precipitation event with total amount of 85 mm, was observed. Although all three tree species were at comparative levels of low water potential, reaching nearly to permanent wilting point, the reaction was substantially different in between tree species. Again the spruce exhibited only small increase in soil water potential, while beech and larch trees reacted with significant increase.

The recharge period is more diverse between individual years. In general, beech and larch stands repeatedly reached saturated conditions during spring in all monitored years. Full saturation under spruce was observed only briefly, for approximately one month during the spring of 2024.

In 2023, the recharge period occurred since mid October and gradually increased until full saturation for beech and larch trees at the end of the year, while the spruce started the new season with a mean deficit of -10 kPa. However, in years 2025 and 2026 the mean soil water potential values in spruce were dramatically low at -100 kPa.

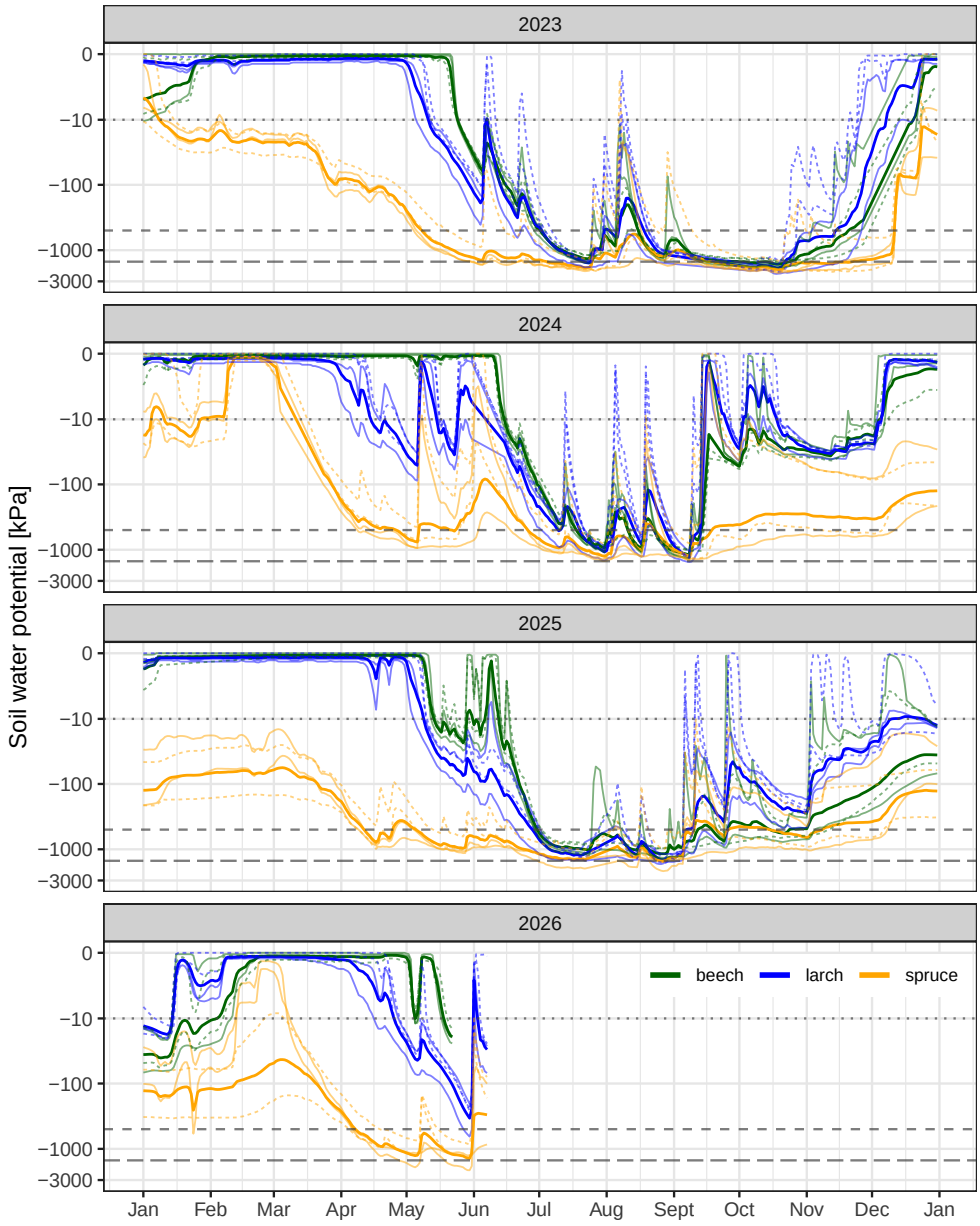


Figure 5.15: Seasonal dynamics of soil water potential (kPa) measured by TEROS 21 sensors under beech, larch, and spruce stands during the monitoring period 2023–2026. Thick lines represent the mean soil water potential for each tree species, thin lines represents individual sensors, depth is distinct by linetype, where soild represents 10 cm and dashed 30 cm. Horizontal dashed lines denote selected thresholds of soil water availability: pF 2 (field capacity, 10 kPa), pF 3.7 (reduced water availability, 500 kPa), and pF 4.18 (permanent wilting point, 1500 kPa).

6

Discussion

Understanding the water and forest relation is increasingly important under changing climate as this close connections actively affect the microclimate, hydrology and functions of our landscape. The main aim of this study was to describe and compare soil moisture dynamic in monocultural forest stands of beech, larch and spruce. This aim was achieved by analysing soil moisture dataset obtained from a newly established soil microclimate monitoring network. In the following sections the results will be discussed with regard to research question stated in introduction.

6.1 Patterns of soil moisture dynamic under beech, larch and spruce

A general repeating pattern of winter water recharge and spring soil moisture depletion was observed across all tree species. However, there were substantial differences in the timing, magnitude and duration of these periods, leading to statistically significant differences in surface soil moisture levels among tree species. While the minimum values of soil moisture were repeatedly observed across all species in summer, the maximum soil moisture values were more diverse between species and individual years.

6.1.1 Early spring period

The most pronounced differences in soil moisture levels were observed in spring period, originating between evergreen spruce and deciduous beech and larch trees. While the soil moisture levels under spruce stands were repeatedly observed to decrease early in February, under beech and larch trees, the soil moisture levels did not decreased until late April to early May. Since the spruce is an evergreen tree, its year round foliage enables to enter the vegetation season earlier. In contrast, the phenology of deciduous trees restricts the water depletion until the emergence of foliage. This is consistent with results reported by (Schume et al., 2003), who in spring observed a decreased surface soil moisture levels under spruce trees when compared to beech trees and attributed this to the earlier transpiration onset of spruce trees, while beech trees remained in dormant period until the foliage emergence. During the dormant period the soil is able to recharge its storage capacity that will provide water resources for

upcoming vegetation season. The phenology of deciduous trees enables longer period of soil water recharge. Urban et al. (2015) reported that the sapflow in beech was strongly connected to tree phenology and the onset of sap flow began with 50% of the first leaves in late April. Therefore, the spruce trees are using its water resources already 3 months in advance, while the deciduous trees remain this period still in the recharge phase.

While the depletion of water in spruce occurred early, the rate was rather moderate, suggesting a regulation of transpiration rate by temperature in early spring. This interpretation is consistent with sap-flow observations in mature Norway spruce, where Matisons et al. (2017) reported, that in spring, the transpiration rate increased after the temperature rise in March. In many studies, the measurement of the transpiration in the period from November to April is often excluded, leading to underestimation of water requirements of spruce. However, (Matisons et al., 2017) also reported that the sap flow in spruce was detected during all year, suggesting a year-round activity of spruce trees. In contrast to moderate and early drawing of spruce, the deciduous trees showed a rapid decline of soil moisture after its start, indicating that the transpiration in deciduous trees is restricted by the phenology.

6.1.2 Summer period

During the first months of the year the spruce had significantly lower shallow soil moisture levels than beech and larch. However, rapid depletion of deciduous trees soon resulted in convergence of shallow soil moisture levels across tree species. In summer the soil moisture was approximately the same level across the stands. This possibly indicates a limit of water availability in shallow soil layers, restricting a further decrease. Under limited soil water, spruce manifests an isohydric stomatal regulation, restricting additional drawing by stomatal closure. This was repeatedly observed for example by (McDowell et al., 2008; Zavadilová et al., 2023). Conversely, the rather anisohydric beech and larch are expected to continue draining the soil, creating a more negative suction pressure. While this was not observed in the shallow soil layers, the deeper soil layers were considerably different from spruce. Since the deeper root systems, beech and larch trees were able to draw water from deeper soil layers, presumably resulting in increased water consumption in summer. This is consistent with findings of Zelíková et al. (2025), who reported, that in summer period the pronounced transpiration of beech trees when compared to spruce trees, depletes more soil water and may contribute to the severity of summer drought. On the other hand, while the shallow root system of spruce restrict the water consumption, as the tree is not able to draw water from deeper soil layers, it is likely to get under water stress earlier, as it rely on its shallow soil moisture resources. Moreover, since the spruce starts to use its water from early spring, in case of decreased precipitation, its water resources are significantly limited.

6.1.3 Recharge period

Starting from November, the soil water levels increased again, slowly building up the difference in soil moisture levels among tree species. The spruce showed a significantly shorter recharge period of consistently increasing soil moisture from November to February. In contrast, the deciduous trees had nearly double the length (until start of May), restricting their main water drawing until foliage emergence.

As the transpiration of deciduous trees is again restricted by the leaf senescence, the soil reservoir enters the recharge period. This is consistent with the sapflow measurements of Urban et al. (2015). In spruce, transpiration in winter is suppressed by decreased radiation, low air and soil temperatures and low atmospheric evaporative demand. However, under mild winter conditions, additional water might be needed. This is supported by the Augustaitis and Pivoras (2024), who reported a transpiration flux, measured by sap flow during temporary winter thaws. With the prolongation of the vegetation season, mild late autumn conditions may further contribute to increase the water requirements of spruce trees.

In case of sufficient precipitation, increased growth of trees would be beneficial. However, under a tight hydrological balance, this possibly shows one of the disadvantages of evergreen trees in lower altitudes. Ponocná et al. (2016) stated that rising temperatures are promoting tree growth, but only to a limit of sufficient water. Since with the changing climate the temperatures are expected to increase (IPCC, 2023), the recharge period of soil under spruce trees will presumably reduce even more.

Moreover, the year round foliage of spruce trees further decrease the water recharge by the canopy interception. As the proportion of interception is determined by the rain characteristics (Staelens et al., 2008), particularly during a low daily amounts this may further significantly reduce the water recharge under spruce trees. Such period was observed in spring of 2022 and described in (Kuželková et al., 2024). Although in total, this period was not prominently under normal, the rain was distributed in small daily amounts, possibly contributing to the decreased recharge under spruce trees. This suggests that the distribution of rain it self is further important particularly to evergreen trees with year round canopy.

Soil water recharge is significantly affected by the infiltration process, integrating soil properties and root systems of tree species. As the shallow and lateral root system of spruce, does not form suitable conditions for preferential flow, the infiltration and soil recharge is limited. This is supported with findings of Jačka et al., 2021, where spruce forest produced significantly lower values of saturated hydraulic conductivity than oak forest. In contrast, the deeper root system of beech and larch trees is likely to contribute to more effective recharge, further promoted by the leafless period of deciduous trees. These observations are consistent with findings of Schwärzel et al. (2012), reporting an effective

recharge in beech trees induced by their crown and root architecture.

Soil moisture dynamic in spruce trees predominantly takes place in the shallow soil layer, while the soil under beech and larch trees is connected with deeper soil layers. Although during summer these layers are depleted, in recharge period these layers are able to replenish before the start of new vegetation season. This further supports an effective recharge mechanism of deciduous trees.

For future conditions an uneven distribution of precipitation is expected. This is supposed to include a periods of drought and extensive rainfall, while keeping the annual amounts comparable (IPCC, 2023). This stresses the need for effective soil water recharge, to sustain vegetation water requirements for the dry periods.

6.2 Interannual variation and soil water potential

Although a general species-specific pattern was prominent and repeated through monitored years, an interannual variability was observed. Since the timing of the transpiration onset in spruce depends on meteorological conditions of given season, it is tightly connected to temperature. Although deciduous trees are restricted until the development of foliage, their phenology also depends on temperature. This is supported by Piao et al. (2015), who showed that the timing of leaf unfolding is triggered by the daytime temperature. In warmer spring, the leaf phenology of deciduous trees may be advanced ahead of time. Therefore, the interannual variability is more prominent in spring period, reflecting the conditions of current year.

Particularly extreme conditions were observed in the year 2024. This year was marked as the warmest on record for Czech republic (Czech Hydrometeorological Institute, 2025) and even for Europe. While the vast majority of the year was over the temperature normal, particularly extreme temperatures were observed in February. On average across the Czechia, the temperature was 6.2°C higher than long-term normal (Czech Hydrometeorological Institute, 2025). Subsequently, even March temperatures were still very prominent, accounting for more than 3°C above normal. These extreme conditions accelerated the onset of spring season. At some locations across Czechia the leaf unfolding appeared almost a month prematurely (Czech Hydrometeorological Institute, 2025).

In this year, larch stands showed a substantial shift in the timing of soil moisture depletion. Although larch trees are deciduous and generally follow the soil moisture regime of beech, this time, the early spring soil moisture dynamic resembled to evergreen spruce. However, the levels in larch were still significantly higher until May. Since the larch trees are light demanding, the forest stands include an understory vegetation. In contrast, the beech and spruce trees does not have such vegetation (for illustration see photo-gallery in

Appendix). This understory layer in larch likely contributed to the early spring soil moisture depletion on top of the shift in phenology. Balandier et al. (2022) reported that the understory vegetation may contribute up to a one third on the total stand evapotranspiration. The spring of 2024 illustrates, that the change in spring temperatures may significantly affect the normal soil water regime of forest.

Similar anomaly was observed in the spring of 2026. This time, the spring temperatures were above normal only slightly, however the spring precipitation was substantially under normal from March to May and possibly affected even the soil moisture levels under beech trees. This suggest, that on top of the temperature anomaly also the precipitation deficit in spring may alter the typical course of forest soil moisture.

Remarkably low interannual variability in shallow soil layers was observed during the summer months. As mentioned in previous section, this likely suggest that soil water availability is repeatedly reaching a limit, resulting in stress on vegetation. This is further supported by the soil water potential measurements, that show in summer months a values reaching to a limit of permanent wilting point (-1500 kPa). Šrámek et al. (2019) reported similar values of soil water potential in Norway spruce forest during particularly hot and dry year of 2018. This year was later linked with prominent tree mortality in Central Germany (Obladen et al., 2021). Under prolonged severe water stress, trees may start to show an early signs of severe water stress, such as defoliation, growth reduction or dessication (Bréda et al., 2006). While suggesting a severe water limitation, the permanent wilting point is a general value used for large variety of vegetation, therefore some degree of adaptation and differences is expected for studied trees.

In the autumn of 2023 severe conditions reaching the permanent wilting point persisted until October. This mirrored in the unusually low soil moisture levels across all species in September and October. This situation presumably originated in the significant summer deficit of precipitation. Fortunately, the last months of 2023 were above precipitation normal and enabled the recharge of soil water before the unprecedentedly warm spring of 2024. However, since the rise of compound drought events in Central Europe (Markonis et al., 2021), we may expect the interaction of decreased precipitation with periods of increased temperatures have substantial effect on soil moisture.

The year 2024 brought another significant event. The precipitation in mid September resulted in prominent floods over some regions of Czechia. Although the Amalie location was only partially affected, over the 4 days the rain accounted for approximately one sixth of the annual total. While in beech and larch trees this event substantially replenished the soil water, in spruce, this was reflected only partially. This is presumably due to a different recharge ability among the tree species. While the mineral soil conditions are comparable across stands, they are altered by the tree litter, organic soil layer and root

systems.

Presented results showed, that the shallow and deeper soil layers under spruce trees are weakly connected. In case of high intensity precipitation and sloping terrain, the water presumably flows laterally in the top horizon, restricting the soil recharge. This is consistent with biomat flow reported in soil under spruce trees by Valtera et al. (2023). Together with the shallow roots system, the recharge of water is presumably significantly decreased in spruce trees.

6.3 Soil water storage and water availability

The observed soil moisture dynamics reflected in total soil water storage across the monitored profile. During the first half of the year, total water storage was lowest under spruce, while beech and larch retained more water. After the onset of seasonal depletion under the deciduous stands, these differences gradually diminished. During summer, the total water storage under beech and larch trees decreased below the levels observed in spruce. This pattern is consistent with (Zelíková et al., 2025), who reported greater summer soil water depletion under beech than under spruce. The pronounced depletion observed under beech and larch extended into the deeper soil layers, suggesting that water uptake by these species affected a larger proportion of the monitored soil profile. This is presumably due to beech and larch deeper root systems and high transpiration rate.

However, by the end of the year, the profiles under beech and larch were able to replenish and at the beginning of the following year they again contained more water than the soil under spruce. Therefore, the water used in summer season was able to recharge during the dormant period. In contrast, although under spruce the soil water storage in summer was higher, mainly due to the contribution of deeper soil layers, the shallow soil layers (0-30 cm), still had a deficit in the beginning of following year as showed in the soil water potential. This indicate that soil under spruce trees was not able to fully recharge, presumably due to combined effect of late transpiration and decreased recharge ability induced by interception and soil properties.

These results show a more dynamic soil water storage under beech and larch trees, supporting a strong recharge and depletion period distinction. In contrast, under spruce the soil water storage dynamic is more conservative and stable, as the distinction of the recharge and depletion periods is less pronounced and more spread out over the course of the year. Since tree species substantially influence the forest water balance, these contrasting hydrological regimes are likely to be reflected in the wider ecosystem, potentially affecting understory vegetation, microbiota and soil formation.

Although total soil water storage is hydrologically important, its ecological relevance also depends on whether the stored water occurs within the effective

rooting zone and remains accessible under the prevailing soil hydraulic conditions (Stocker et al., 2023). Consequently, the comparatively higher summer water storage under spruce might not be reflected in tree vitality. Because the root system of spruce is generally concentrated within a relatively shallow soil layer, spruce may have limited access to water retained in the deeper parts of the monitored profile. This restricts the effective soil water reservoir available to the trees and may increase their dependence on water stored in the upper soil layers and on recent precipitation. In contrast, the deeper and more extensive rooting systems of beech and larch may allow to use water from a larger portion of the soil profile. Although this contributes to stronger summer soil water depletion, access to a larger effective rooting-zone water reservoir may represent an important adaptive strategy supporting tree functioning during dry periods under a changing climate.

6.4 Tree traits under changing climate

Studied tree species represent contrasting ecohydrological strategies, that reflect in characteristic traits adapted to the conditions of their natural environment. While some of those might turn out to be beneficial under changing climate, other might contribute to limitations of their future distribution. As natively mountainous tree species, spruce is adapted to rather mild temperature conditions with sufficient amount of precipitation. Therefore, neither its crown and foliage, nor root system, did not have to adapt to cope with droughts and high temperatures. Since higher temperatures increase the water requirements, the precipitation might no longer be sufficient to sustain its growth in lower altitudes. In the past years, a reports of spruce mortality linked to drought increased, therefore with the predictions of future climate we may expect to see more of spruce forest dieback, particularly in locations with limited water conditions. As Čermák et al. (2021) proposed, the suitable conditions for spruce growth in Czechia will presumably retreat to mountain areas again.

Larch as the European only coniferous tree has a unique position. While also originating in mountains, this tree developed a deciduous phenology. While, this was presumably rather for protection from winter desiccation when the soil is still frozen, it might transfer to serve as a water saving strategy. Since larch trees are highly light demanding, the basal area per hectare of such forest is lower than in case of its competitors. This might possibly affect the timber yields. However, the deciduous nature helps to decrease the restriction of water recharge via interception. Moreover, the heart root system of larch possibly contributes to increased soil infiltration. This study suggested its possible sensitivity to extreme spring conditions of drought and temperature. However, only little is known about the hydrology of larch forests, therefore a further research in this regard is needed to understand its possible advantages or flaws under changing climate.

Representing the only tree species that natively occurs in the area of Amalie, the beech inherited specific traits, that seems to serve as an adaptive advantages at lower altitudes. With the limitation of transpiration by foliage it provides a long period of soil water recharge. On the other hand, since this restriction, beech has limited period to leverage its growth. This is at the expense of a high summer water consumption reaching to deeper soil layers. Under insufficient winter and spring precipitation this could possibly bring issues. However, its architectural traits of crown, stem and roots forms a synergy for effective soil water recharge, described as double funnelling effect (Schwärzel et al., 2012). This trait could possibly further gain its importance with the expected uneven precipitation distribution, transporting a high amounts of water to soil reservoir, while reducing the surface runoff, erosion and subsequently flash floods. However, even beech trees in its native environment are reported to be negatively affected by the changing climate (Walthert et al., 2021). Therefore forests in Central Europe might need even more pronounced transformation. Since the climate is changing the conditions, the idea of forests composed of native tree species might no longer be sustainable. An assisted migration of non native tree species, reflecting their adaptive traits and strategies, might promise a climate resilient forests. While a careful consideration of ecological connections is required, the services provided to society by healthy forests are irreplaceable.

6.5 Advances and limitations

The establishment of the new soil microclimate monitoring network provided valuable methodological and scientific insights. Since primary field data form an essential foundation for environmental research a high quality standards were followed. A careful consideration of experimental design formed a setting for separate replicates at three individual locations, while maintaining comparable soil and meteorological conditions across the studied forest stands. Nevertheless, several methodological simplifications and practical decisions were necessary to obtain a consistent and usable dataset. These limitations are discussed below. Finally, as the soil moisture and microclimate dataset collected at the Amálie site provides a basis for further research, the future potential of the monitoring network is outlined.

6.5.1 Monitoring network and maintenance

A substantial part of this thesis was dedicated to the establishment and maintenance of a forest soil monitoring network. This network enabled the collection of a large soil dataset with over six years of continuous monitoring. Since reliable primary data are essential for obtaining valid insights, particular attention was paid not only to data analysis, but also to understanding the technical limits of the sensors, field installation, and routine operation of the

monitoring stations.

An important part of this work was the development of a standardisation procedure for TMS stations. Initially observed differences among signals obtained from individual TMS stations motivated a closer investigation of station behaviour. The findings were discussed with the manufacturer and contributed to improvements in the manufacturing process. In consequence, the current generation of TMS stations now produces more consistent measurements under comparable conditions.

A further step was taken with the construction of soil-specific calibration equations. The default calibration curves, based mainly on mineral soils, were considered insufficient for the studied forest soils because of the high organic matter content in the upper soil layer. Therefore, soil-specific calibration equations were derived to improve the relevance of the measured volumetric soil moisture values for the studied conditions. The knowledge gained during this process was later used in collaboration with the manufacturer and contributed to the preparation of the Calibration Handbook (Jačka et al., 2023).

The monitoring network required continuous maintenance throughout the study period. Correct sensor placement and close contact between the sensor body and the surrounding soil were essential for reliable measurements. Loose contact between the sensor and soil may introduce bias into the measured values. Such gaps may lead to an underestimation of soil water content under dry conditions. Conversely, during precipitation events, water may preferentially accumulate around the sensor, causing an overestimation of the signal values.

Such behaviour was observed in some raw 15-minute records, where several stations showed an unusually rapid soil moisture response, probably related to imperfect contact between the sensor and the surrounding soil. This issue was addressed through regular field checks, inspection of sensor stability, protection against disturbance by wildlife, and aggregation of the data to daily values, which reduced the influence of short-term artefacts. These observations highlight the importance of careful sensor installation and regular maintenance when similar monitoring equipment is used.

Despite precautions, several technical problems occurred during the monitoring period. In few cases, stations stopped recording and therefore had to be replaced. As a result, the dataset required thorough inspection before analysis. Erroneous values and sensor failures were identified and removed during data processing. This step was necessary to ensure that subsequent analyses were based on reliable measurements rather than relying on artefacts of field operation or sensor malfunction.

6.5.2 Soil properties

Obtained soil moisture values are directly influenced by the selected calibration equation. An inappropriate calibration may therefore introduce systematic bias into the absolute values of soil water content. For this reason, the strict

soil moisture values should be interpreted with caution. However, because this thesis focuses primarily on soil moisture dynamics, the relative differences and changes, rather than on absolute water content values alone, are important. Moreover, the patterns observed in soil moisture were further supported by independent measurements of soil water potential, which increased the confidence in the interpretation of the dataset.

The soil at the Amálie site is fine-grained, with high silt content, and was classified as Albic Stagnic Luvisol, where the Bt horizon is enriched by clay particles. These soil conditions affect infiltration characteristics, water redistribution within the soil profile, and potentially also rooting depth and root distribution of trees (Crow, 2005). Such soil properties may limit water recharge through the soil matrix and increase the importance of preferential flow pathways. Consequently, the observed differences among tree species may be partly shaped by the specific soil conditions of the site and may be less pronounced in more permeable soils. Further research is therefore needed to compare these patterns with similar forest stands under different soil conditions.

Since the groundwater table at Amalie is at considerable depth, approximately 10–25 m below the studied forest stands, the drawing of trees was considered unlikely. The observed soil moisture patterns are thus interpreted primarily as the result of species-specific differences in precipitation partitioning, infiltration, soil water redistribution, and root water uptake within the monitored soil profiles. However, different conditions may apply to sites with a shallow groundwater table, where capillary rise or root uptake could contribute more substantially to tree water supply.

The results and interpretations presented in this thesis are primarily based on soil data. Soil moisture represents an integrative variable reflecting the combined effects of precipitation input, infiltration, soil water redistribution, root water uptake, and evapotranspiration losses. However, it does not allow these individual fluxes to be directly separated. This limitation is particularly relevant when data are aggregated over longer time steps, as wetting and drying processes may partly compensate for each other and obscure short-term dynamics. However, Schwärzel et al. (2009) showed that a sufficiently dense network of soil moisture sensors mirrors a reasonable approximation of those fluxes within the soil profile. Therefore, although simplified, the soil approach provides insights to the complexity of forest water balance of studied tree species.

6.5.3 Future prospects

The monitoring network is intended to remain in operation in the coming years, which will further increase its scientific value by extending the temporal coverage of the dataset. Longer time series will enable future analyses of interannual variability, drought events, recovery periods, and potential long-term shifts in forest soil moisture regimes. Beyond the scope of this thesis,

the dataset is already being used in environmental modelling, particularly for describing processes related to precipitation partitioning and for developing soil moisture forecasting approaches by neural networks.

Further extension of the monitoring network has already been initiated through measurements of throughfall, while additional measurements of stemflow and sap flow are currently being developed. These extensions will help to address one of the current limitations of the study by complementing soil moisture observations with direct measurements of individual components of the forest water balance. Future studies will therefore be able to move from the interpretation of soil moisture patterns towards the direct quantification and comparison of interception, transpiration, and soil water storage under different tree species.

Although the present study primarily focuses on hydrological aspects, the overall response of the selected tree species to changing climatic conditions further requires information on forest vitality and growth. For this purpose, an additional network of dendrometers has been implemented at the Amálie site. These measurements will provide a basis for evaluating the effects of climatic variability and drought stress on tree growth in a drought-prone region.

In this way, the monitoring network established at the Amálie site provides not only the empirical foundation for this thesis, but also a long-term research infrastructure for studying forest water balance and tree response under changing climatic conditions.

7

Conclusions

In the context of ongoing climate change, prolonged vegetation seasons and increasing evapotranspiration demand are expected to intensify the requirements on forest water resources. Current forest state reflects conditions and management decisions made based on the past climate. However, these conditions are already changing. Over a hundred years are required to grow a forest, therefore, forest management practices need to account not only for past and current conditions but also for the future. Since, water availability may become one of the limiting factors for forest vitality a consideration and understanding of water requirements and recharge ability associated with different tree species is needed.

This thesis provides evidence of significant differences in soil moisture dynamics among three contrasting tree species commonly planted in Central Europe: European beech, European larch and Norway spruce. The established soil monitoring network showed that these differences were consistently occurring across monitored years (2021 - 2026). The most pronounced differences in surface soil layers were observed during spring, when soil moisture under spruce repeatedly started to decrease months before beech and larch forest. In contrast, beech and larch stands generally maintained higher soil moisture during the leafless period and delayed the main seasonal depletion until foliage development. However, in deeper soil layers, soil moisture in summer months was considerably lower in beech and larch trees. Consequently, the total water storage in the soil profile down to -115 cm, was since summer lower under beech and larch trees when compared to spruce stands. Nevertheless, this summer deficit was replenished during the following winter recharge period, whereas soils under spruce showed a only limited recovery.

Under the studied drought-prone conditions, the evergreen character of spruce appears to represent a considerable disadvantage for soil water recharge. Its year-round canopy cover increases the potential for interception losses, particularly during low precipitation events, and reduces the amount of water reaching the soil surface. In addition, early transpiration in spring shortens the effective winter recharge period and contributes to an earlier onset of soil water depletion. By contrast, the deciduous character of beech and larch allows a longer period of reduced canopy interception and limited transpiration during winter and early spring, which supports soil water recharge before the onset of

foliage development.

Several observations related to soil water infiltration may further contribute to the observed species-specific soil moisture patterns. The organic layer under spruce is likely less integrated with the mineral soil and may form a sharper interface between organic and mineral horizons. In gently sloping terrain, this can potentially promote shallow lateral subsurface flow within the organic layer and thus reduce vertical infiltration into deeper soil layers. By contrast, the deeper rooting systems of beech and larch may provide preferential pathways that enhance vertical redistribution of water. In beech stands, this mechanism may be further supported by the double funnelling effect associated with canopy structure, stemflow and root-induced preferential flow. These mechanisms were not all directly quantified in this thesis, however provide a plausible process-based interpretation of the observed soil moisture patterns.

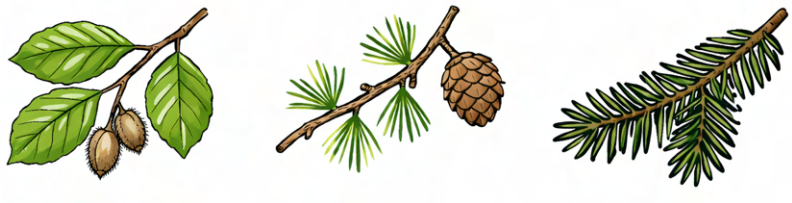
Although the species-specific patterns were generally consistent across the years, the results also showed that they can be modified by meteorological anomalies. This was particularly evident in 2024, when soil moisture under larch decreased shortly after spruce and substantially deviated from its typical spring pattern. In beech, the pattern was less affected, although earlier foliage development was accompanied by an earlier decrease in soil moisture. In larch stands, the early depletion may have been further amplified by understory vegetation. These findings indicate that extreme years can alter the water balance of forest stands and may change the timing and intensity of soil water depletion.

Overall, this thesis answered the formulated research questions by demonstrating that soil moisture dynamics differ considerably among the studied forest monocultures. These differences are likely to be interpreted through species-specific traits affecting precipitation partitioning, soil water recharge, water redistribution and uptake. Therefore tree species composition should be considered in hydrological assessments and climate-resilient forest planning.

The current state of forests in Central Europe reflect past climatic conditions. Therefore an insights of forest reaction to climate changes are needed in order to sustain forest vitality. This monitoring network located in a drought-prone area Amalie, provides an opportunity to study these ecosystems under foreseen climatic conditions expected for Central Europe. The gained knowledge therefore provide foundational evidence for decision making and designing a future climate-resilient forests. Moreover, it shows the course of development of contemporary forests.

At the same time, soil moisture represents only one part of forest drought resilience. Although this thesis showed pronounced species-specific differences in soil water dynamics, their direct impact on tree vitality, growth and long-term ecosystem stability needs to be evaluated. Further research should therefore link soil moisture monitoring with indicators of tree health, growth and drought stress response. For this purpose, the soil monitoring network established at

the Amálie site provides a suitable basis for future research on the interaction between soil water dynamics, tree species composition and forest resilience under changing climatic conditions in Central Bohemia.



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A

Appendix

Forest stands

Figure A.1: Spring in beech forest stand at location 1. The forest floor is covered in tree litter.

Figure A.2: Spring in larch forest stand at location 1. The understory is abundant and diverse.

Figure A.3: Spring in spruce forest stand at location 3. The forest floor is covered by thin layer of tree litter.

Figure A.4: Winter in beech forest at location 1. Forest floor is completely and uniformly covered by snow.

Figure A.5: Winter in larch forest at location 1. Forest floor is completely and uniformly covered by snow.

Figure A.6: Winter in spruce forest at location 1. The snow cover is thin with apparent gaps.

Location variability

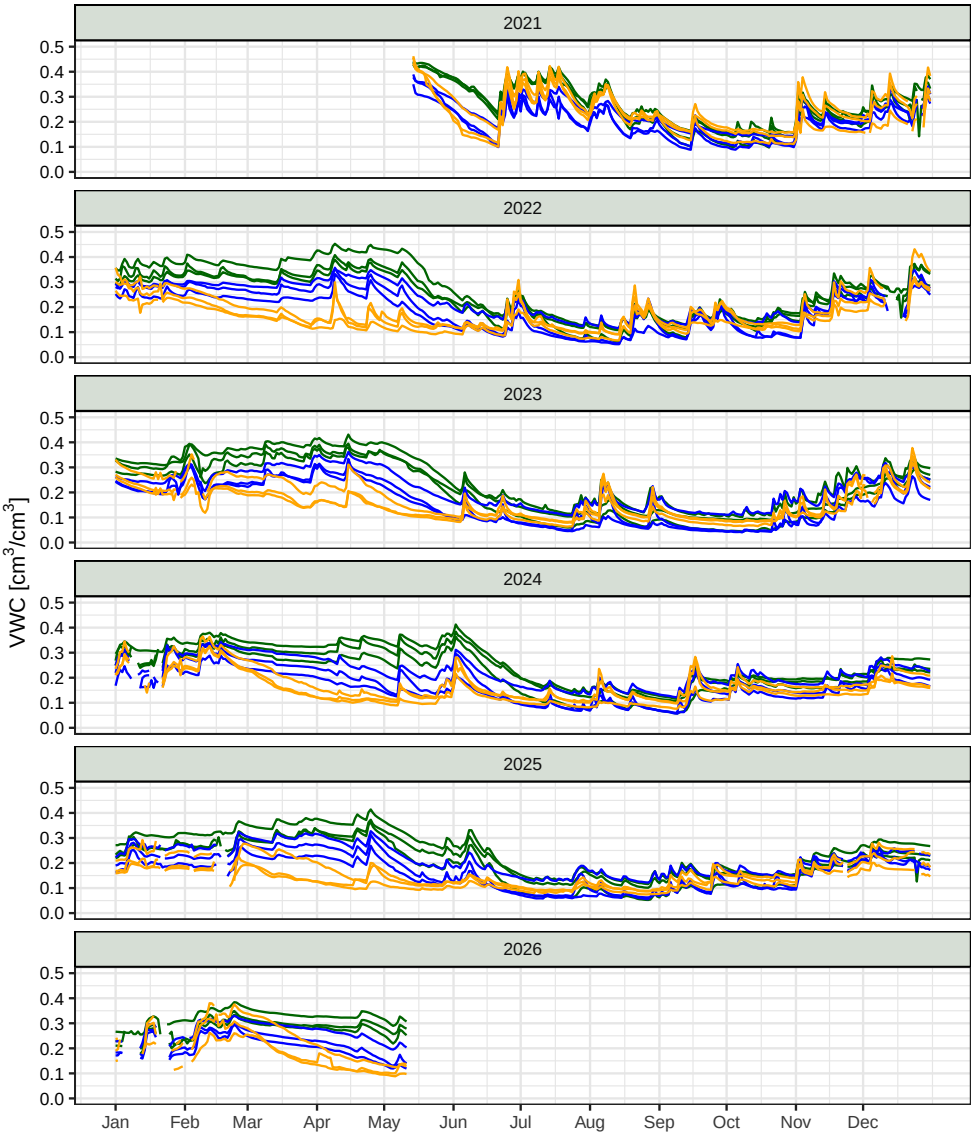

Figure A.7: Seasonal dynamics of soil moisture in the topsoil layer (0–15 cm) for individual years (2021–2026).

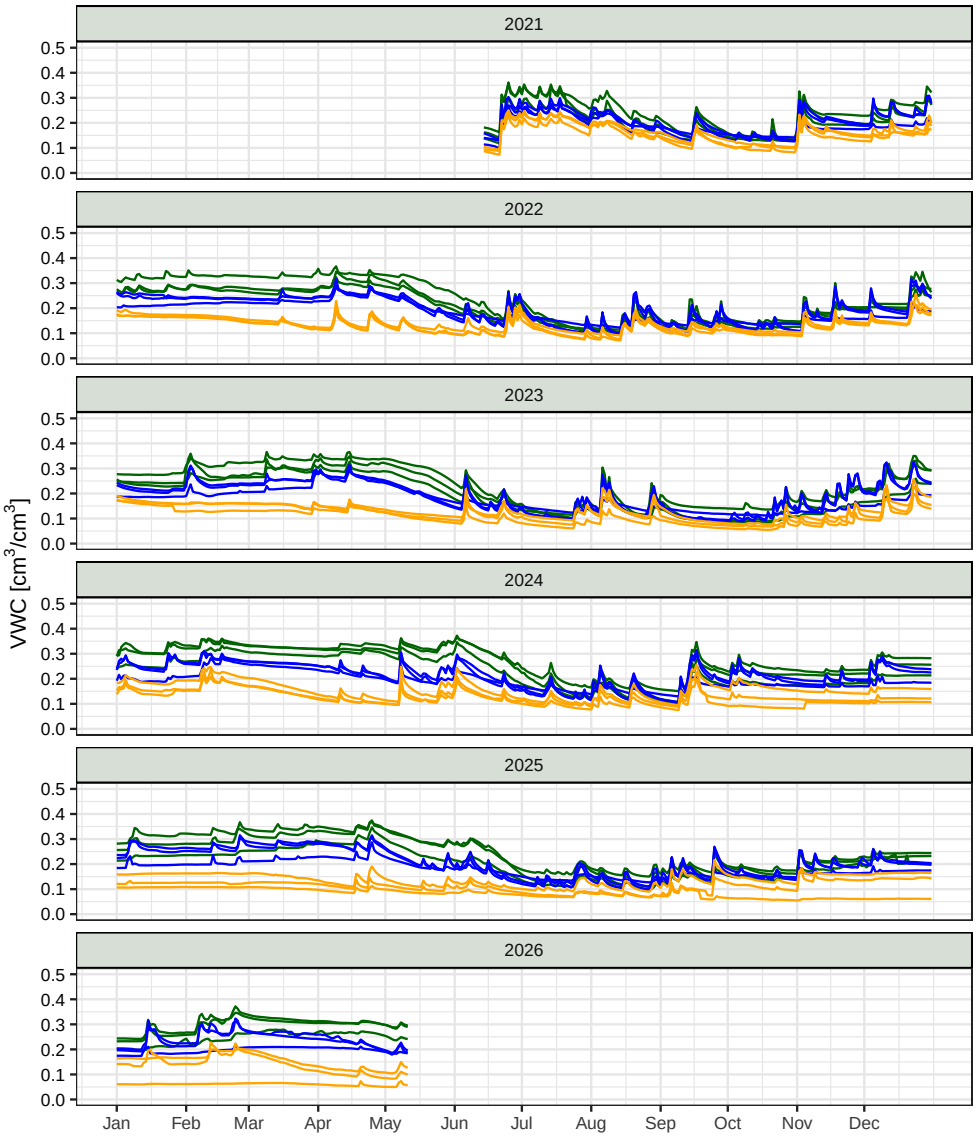

Figure A.8: Seasonal dynamics of soil moisture in the subsoil layer (15–30 cm) for individual years (2021–2026).

Monthly soil water storage

Table A.1: Monthly mean soil water storage by soil layer and tree species in 2024.

Tree species	Layer (cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beech	0-15	–	–	–	–	47.2	41.3	21.1	18.7	22.0	28.2	28.5	36.7
	15-30	–	–	–	–	46.9	42.9	25.2	23.8	29.0	32.5	31.2	37.1
	30-50	–	–	–	–	57.5	54.9	41.5	39.6	45.0	45.3	44.3	49.4
	50-70	–	–	–	–	97.6	99.3	77.6	73.6	84.0	85.7	83.5	85.4
	70-90	–	–	–	–	75.7	83.5	71.9	64.7	68.5	71.2	68.1	67.6
	90-115	–	–	–	–	80.3	98.8	88.8	81.9	91.9	92.9	86.1	83.4
	Total	–	–	–	–	**405.2**	**420.7**	**326.1**	**302.3**	**340.4**	**355.8**	**341.7**	**359.6**
Larch	0-15	–	–	–	–	26.1	26.5	15.9	17.0	19.8	24.7	24.7	32.3
	15-30	–	–	–	–	32.1	31.0	21.6	23.3	27.7	30.7	27.9	33.6
	30-50	–	–	–	–	47.6	50.1	41.6	43.1	47.9	45.7	43.1	47.0
	50-70	–	–	–	–	88.1	94.4	84.2	83.7	90.3	89.4	84.3	85.4
	70-90	–	–	–	–	72.5	77.8	70.0	70.3	72.7	72.3	66.5	66.9
	90-115	–	–	–	–	71.8	88.1	76.7	80.0	89.7	86.4	79.8	79.0
	Total	–	–	–	–	**338.2**	**367.9**	**310.0**	**317.4**	**348.1**	**349.2**	**326.3**	**344.2**
Spruce	0-15	–	–	–	–	18.7	22.6	16.0	17.7	20.4	24.1	22.3	28.5
	15-30	–	–	–	–	20.1	21.5	15.6	17.7	20.9	21.1	18.7	20.0
	30-50	–	–	–	–	43.4	52.2	44.6	46.4	51.4	50.6	47.2	47.4
	50-70	–	–	–	–	77.3	94.7	87.9	90.5	97.8	99.2	93.8	91.6
	70-90	–	–	–	–	62.7	75.5	73.6	76.6	82.5	83.9	80.3	78.1
	90-115	–	–	–	–	73.0	82.6	80.2	83.2	95.2	95.0	89.6	89.0
	Total	–	–	–	–	**295.2**	**349.1**	**317.9**	**332.1**	**368.2**	**373.9**	**351.9**	**354.6**

Note: Values represent monthly mean soil water storage in mm. Missing values are indicated by –.

Table A.2: Monthly mean soil water storage by soil layer and tree species in 2025.

Tree species	Layer (cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beech	0-15	41.7	44.3	48.8	51.1	40.1	32.3	17.5	16.9	20.9	21.3	31.0	37.4
	15-30	40.7	43.0	45.9	48.7	41.9	34.3	21.7	20.7	25.1	24.5	30.3	34.3
	30-50	51.9	53.2	56.2	59.0	51.1	43.0	36.3	35.5	39.6	38.3	44.5	46.3
	50-70	88.6	91.2	96.1	100.8	93.8	78.4	67.9	66.6	70.7	70.2	70.3	75.0
	70-90	68.3	69.8	74.6	79.0	77.6	65.4	54.9	52.4	56.6	56.3	55.7	56.4
	90-115	82.6	82.7	84.5	89.8	92.2	83.1	63.8	58.9	66.1	64.6	67.3	67.3
	Total	**373.8**	**384.2**	**406.1**	**428.4**	**396.7**	**336.5**	**262.1**	**251.0**	**279.0**	**275.2**	**299.1**	**316.7**
Larch	0-15	34.3	34.8	39.7	38.4	26.3	20.9	14.6	14.4	19.0	18.9	28.7	32.9
	15-30	36.1	37.2	39.3	39.5	31.1	26.1	20.8	20.0	25.3	23.2	28.5	30.1
	30-50	49.5	50.2	52.5	52.9	46.7	42.0	37.4	37.0	41.4	39.8	41.3	41.9
	50-70	87.1	88.1	90.0	91.7	88.4	81.4	73.9	73.0	80.7	80.2	81.7	81.6
	70-90	67.9	68.8	70.5	72.8	71.6	65.6	58.4	57.1	64.5	62.7	62.8	62.9
	90-115	78.9	78.9	79.5	81.6	81.2	74.9	68.2	66.3	79.4	75.0	73.1	72.9
	Total	**353.8**	**358.0**	**371.5**	**376.9**	**345.3**	**310.9**	**273.3**	**267.8**	**310.3**	**299.8**	**316.1**	**322.3**
Spruce	0-15	30.3	28.9	27.2	20.4	17.3	17.7	14.4	14.3	18.8	19.9	26.7	31.4
	15-30	20.3	20.4	19.7	17.7	16.0	15.8	13.4	13.6	17.7	17.0	20.5	20.9
	30-50	46.9	46.6	45.8	43.7	42.3	41.6	38.8	40.0	46.4	45.3	46.0	44.6
	50-70	90.3	89.6	88.3	83.9	82.6	81.8	75.0	76.3	86.6	85.2	86.0	83.2
	70-90	76.5	75.5	74.7	73.2	72.3	71.8	63.4	67.2	77.5	74.6	76.2	72.1
	90-115	85.5	84.3	83.5	83.3	82.1	82.5	75.9	82.2	89.9	86.7	86.9	82.2
	Total	**349.8**	**345.3**	**339.2**	**322.2**	**312.6**	**311.2**	**280.9**	**293.6**	**336.9**	**328.7**	**342.3**	**334.4**

Note: Values represent monthly mean soil water storage in mm. Missing values are indicated by –.

Table A.3: Monthly mean soil water storage by soil layer and tree species in 2026.

Tree species	Layer (cm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beech	0-15	39.5	47.7	46.9	45.3	–	–	–	–	–	–	–	–
	15-30	35.9	43.1	45.0	43.7	–	–	–	–	–	–	–	–
	30-50	48.6	53.5	54.8	54.0	–	–	–	–	–	–	–	–
	50-70	80.1	89.4	95.8	95.3	–	–	–	–	–	–	–	–
	70-90	61.0	68.7	72.5	72.3	–	–	–	–	–	–	–	–
	90-115	69.3	74.1	76.2	76.7	–	–	–	–	–	–	–	–
	Total	**334.4**	**376.5**	**391.2**	**387.3**	–	–	–	–	–	–	–	–
Larch	0-15	32.6	40.3	38.1	31.4	–	–	–	–	–	–	–	–
	15-30	31.8	37.3	37.0	33.4	–	–	–	–	–	–	–	–
	30-50	43.1	47.8	50.1	47.4	–	–	–	–	–	–	–	–
	50-70	82.2	86.3	93.7	91.2	–	–	–	–	–	–	–	–
	70-90	63.3	70.9	76.8	72.4	–	–	–	–	–	–	–	–
	90-115	72.7	73.4	74.9	75.6	–	–	–	–	–	–	–	–
	Total	**325.7**	**356.0**	**370.6**	**351.4**	–	–	–	–	–	–	–	–
Spruce	0-15	31.4	40.8	32.3	19.6	–	–	–	–	–	–	–	–
	15-30	21.6	24.6	21.5	15.3	–	–	–	–	–	–	–	–
	30-50	46.3	48.9	47.2	41.7	–	–	–	–	–	–	–	–
	50-70	84.9	88.8	86.1	75.7	–	–	–	–	–	–	–	–
	70-90	73.7	76.1	72.7	63.0	–	–	–	–	–	–	–	–
	90-115	82.8	85.6	83.8	75.2	–	–	–	–	–	–	–	–
	Total	**340.7**	**364.8**	**343.6**	**290.5**	–	–	–	–	–	–	–	–

Note: Values represent monthly mean soil water storage in mm. Missing values are indicated by –.

List of Figures

Appendix

List of Tables