# Background

## Peatlands

### Definition

Peatlands are special terrestrial and wet ecosystems which developed under waterlogged conditions. The absence of air and thus oxygen prevents dead organic matter (e.g. litter or dead roots) on or under the ground from rotting and eventually to be decomposed by microorganisms in the soil (Joosten and Clarke 2002). Instead, the anaerobic environment leads to the development of peat – a type of soil with an organic material content of more than 30 % (Blum 2020). In contrast to mires, peatlands do not completely dry out periodically which avoids the decomposition of peat (DWS 2022). This provides an ideal environment for the sustainable accumulation of peat to build up the characteristic peat horizon with a thickness of more than 30 cm (Blum 2020; AG Boden 2005). Still, the water level of peatlands is oscillating as well but due to large pores within the peat and floating vegetation the peat body can absorb and release water by swelling and shrinking (Joosten 1993). This makes the peatland a self-regulating ecosystem and enables it to adapt to altering water availability.

Due to their special characteristics, peatlands build their own soil class in addition to terrestrial, semi-terrestrial, sub-hydric and semi-sub-hydric as well as salt and sodic soils (Blum 2020).

### Classification of peatlands

One peatland is not like another. The development of peatlands is depending on different factors like the climate situation (e.g. the ratio of precipitation and transpiration or the duration and depth of soil frost), the geological characteristics of the subsoil (e.g. water holding capacity), the surrounding environment and the conditions of water source and runoff (e.g. its size, relief, substrate, plant cover and use of the catchment area) (Xintu 2009; Succow and Jeschke 2022). They can be classified into 2 main types and various sub and intermediate types of peatlands which are defined by their origin of water, the water quality and movement and their occurring plant communities.

Bogs are ombrogenous or ombrothrophic peatlands which are fed only by precipitation. They are situated on top of the bedrock without any access to groundwater or other surface water bodies (Burmeister et al. 1990). Subsequently, they are depending on frequent precipitation and specific climatic conditions where the amount of precipitation exceeds the united extraction of water by percolation, runoff and transpiration for them to keep a constant water level (Johnson 1985). Since bogs exclusively receive their water from precipitation, they are rather poor in nutrients which also limits the diversity and amount of vegetation. It mainly consists of sphagnum mosses besides some dwarf shrubs (e.g. heaths), cranberry and thin-leaved sedges (Kaule 1973; Burmeister et al. 1990). Sphagnum mosses are the main driver for peat production in bogs. While the moss is constantly growing upwards, its lower part dies. Due to the lack of nutrients and water movement in bogs, the pH-value and oxygen concentration of the water is rather low (Clymo 1984) which gives them an acidic character and reduces the activity of microorganisms and hence leads to a reduced turnover of the dead organic material. Instead, the organic material accumulates as peat which piles up on top of the bedrock in a convex bulged peat body and causes the ground to grow upwards (Eggelsmann 1990a).

On the contrary, fens are emerging from ground or accumulated surface water due to no or only very little runoff and thus can be found in depressions or lower positions where water is naturally accumulated (Burmeister et al. 1990). They are categorized into topogenous and soligenous fens. While topogenous fens are formed by the paludification of valleys and synclines or the silting up of lakes and ponds, soligenous fens are located at slopes underneath (percolation fen) or directly at the source of streams (spring fen) (Eggelsmann 1990a). Due to their independence from precipitation, fens can also occur in drier regions with less precipitation (e.g. Brandenburg). Unlike bogs, fens do not pile up peat. Instead, the dead organic material is sinking to the ground of the water body which successively leads to accumulation of peat below the water surface (Pickert and Bräutigam 2017). Fens are minerotrophic wetlands and thus can be rich in nutrients depending on the amount of dissolved nutrients in the water which are originating from the bedrock underneath or around the fen’s water catchment area. This and the slight movement of water often leads to a less acidic environment compared to bogs and is favorable for a more diverse society of plant species including various grass species e.g. reeds or Carex sp and even natural wetland forest species mainly consisting of alder trees (Johansen et al. 2018; Schrautzer and Trepel 2014; Burmeister et al. 1990). Furthermore, the moving water in fens is causing a higher oxygen concentration which enhances the activity of decomposers and thus leads to a smaller accumulation of peat.

When environmental conditions change, the peatland type might change as well. This way, a former minerotrophic fen which is increasingly affected by precipitation water and thus can be characterized as ombrominerotrophic, is called a transitional bog (Burmeister et al. 1990). On the other side, when fens dry out, the peat gets in contact with oxygen and the microorganisms will start to decompose it. Then the peatland can turn into a half bog or gley bog soil (Sauerbrey et al. 2002) which is temporarily affected by ground or back water but also dries out from time to time so the content of organic material in the soil is reduce to 15-30 % (Blum 2020).

### Usage and drainage of peatlands

Ever since peatlands started to develop after the last ice age about 10,000 years ago (NABU 2023), they did not play a major role in people’s life. They have primarily been seen as mystical places and were only faced in myths and stories. Furthermore, low nutrient contents and high water levels as well as the impossibility to use them for transportation by terrestrial or aquatic vehicles prevented any economic usage of peatlands for agriculture or construction (Eggelsmann 1990a). In the 18th century, peatlands started to become more important in Germany and central Europe when people realized that drained peatlands provide an additional source of cultivable land for agriculture and its peat could be used as fuel or fertilizer (Müller-Kroehling and Zollner 2015). Since then, the intensity of usage and exploitation has strongly increased. By now, more than 90 % of all peatlands in Europe (Bonn et al. 2015) and 95 % in Germany are drained and ameliorated (Succow and Jeschke 2022).

Today, several studies show that the drainage of peatlands has severe effects on the ecosystems themselves and coupled systems and processes (Eggelsmann and Mäkelä 1964; Höper 2007; Müller-Kroehling and Zollner 2015; Ramchunder et al. 2009; Roulet and Moore 1995; Succow and Jeschke 2022). The water that got drained gets lost from the ecosystem and cannot be provided anymore for the vegetation close by. Without the water, the peat which has not gotten harvested yet for fuel or fertilizer starts to mineralize through the contact with oxygen. Instead of sequestrating carbon from the atmosphere, the peatland becomes a new carbon source when the carbon stored in the peat body is decomposed by microorganisms and released as carbon dioxide or methane. Hutchinson (1980) found that the mineralization of the peat also leads to unequal shrinking of the peatland body’s surface, sometimes even by several meters due to a heterogenous thickness of peat throughout the peatland area. This creates micro reliefs on the peatland surface and the peat body ultimately loses its ability to expand when the water level rises again. With the shrinking of the peatland body, the peatland surface gets lowered and the area’s ground becomes unstable for construction or agricultural land. Besides the instability, the ground water level has changed as well and requires constant drainage and adaptation to avoid waterlogging conditions and ground water impact on the site. Furthermore, the loss of water causes the release of huge amounts of stored nitrogen on alkaline fen sites which leads to an over-eutrophication of the peatland surface and the ground water. On nutrient-poor bog sites, the lack of water increases the mobility of phosphor. Lastly, the drainage of peatlands increases its predisposition towards natural damages by erosion (IUCN Peatland Programme 2023; Li et al. 2018) or even wildfires due to the fuel character of dry peat.

### Importance and restoration of peatlands

Peatlands are the most effective systems when it comes to carbon storage. They are covering less than 3 % of the world’s total terrestrial area (Xu et al. 2018) while storing more than half a trillion tons of carbon (Yu et al. 2010; IUCN UK 2020). This easily exceed the amount of carbon that is stored by all the forests biomass together (Pan et al. 2011). Regarding the production of biomass, peatlands show a comparable productivity as forests in Germany do. Succow and Jeschke (2022) found that bogs, which are solely fed by less nutritious precipitation are producing a biomass of up to 8 t ha-1 a-1 and more nutrient-rich fens can achieve twice the amount within one year. Natural peatlands have an increment of 5 – 15 m3 ha-1 a-1 of peat while they are losing 50 – 250 m3 ha-1 a-1 organic material once they are drained. Meanwhile, the National Forest Inventory shows that forests in Germany, depending on the tree species and their site conditions, are growing by 11.23 m3 ha-1 a-1 on average (Thünen-Institut 2012). The carbon of dead organic biomass from the plants gets preserved within the peat for thousands of years thus it is disposed permanently from the atmosphere until being disturbed (Göttlich 1990). For forests these periods of carbon storage are shorter and usually limited to where the biomass is either harvested or the tree dies and the carbon is released again by burning or decomposition. Besides carbon, the peat also absorbs other elements like nitrogen and phosphor (Göttlich 1990).

Additionally, peatlands are important providers of water to the surrounding landscapes. Due to their water content of up to 95 % (Eggelsmann 1990a; Succow and Jeschke 2022) and the oscillation properties of their peat bodies, these wetlands can help to compensate extreme weather events like buffering excess water during heavy rain and floods or provide humidity and cooling through surface transpiration during droughts and heat periods (Müller-Kroehling and Zollner 2015). The rather nutrient-poor environment of peatlands is furthermore dependent on external nutrient input. Subsequently, it filters all substances from the water including pollutions (Göttlich 1990).

In the 1960s, renaturation measures of peatlands have taken place as a first attempt of biodiversity conservation in peatland areas. About one decade later, also the rewatering of peatlands have been taken into consideration for the first time while the mitigation of climate change effects were progressively coming into the focus of the general public and politics (Müller-Kroehling and Zollner 2015; Rattay et al. 2016).

The restoration of peatlands mainly concludes the process of rewatering, renaturation and regeneration (Eggelsmann 1990b). The rewatering of the peatland is achieved by closing former draining diches to prevent any further drainage of the peatland area (Zollner 1993). Then the peatland area can be flooded again by the water catchment area or precipitation. As a support for the rewetting, silvicultural measures, e.g. thinning of the occurring forest stand, can be applied (Zollner 1993; Zollner and Cronauer 1998). This will increase the water supply from stand precipitation which reaches the ground due to reduced interception effects from the trees. The lower vegetation cover also minimizes the water uptake by wooden species. Additionally, thinning of the forest stand and rewatering of the area support the renaturation of the peatland as well. The lower stocking level of former economic tree species reduces the degree of ground shading and enhances the potential for natural peatland and pioneer species to establish a peatland forest under close-to-nature conditions again (Zollner 1993). In a last step, the water level needs to be raised until a minimum soil depth of 10 cm below the peat body surface (Müller-Kroehling and Zollner 2015) so the peat regeneration sets in and the peatland can be fully revived again (Eggelsmann 1990b).

Yet, restored peatlands will still differ from natural peatlands. Due to the uneven relief coming from the surface shrinking of the drained peat body, the restored peatland cannot be equally rewetted again (Zollner 1993). Some parts of the original peatland area will stay dry which changes the character of the ecosystem. This divers mosaic of microhabitats gives the chance to be used as refuges by species which were better adapted to the former dry conditions of the drained peatland (Müller-Kroehling and Zollner 2015).

In order to fully recover and regain its natural conditions, the rewatered peatland needs to face a long-term succession (Succow and Jeschke 2022). Nowadays, this has become more challenging because of the very intensive usage and altered climatic conditions. The drained peatlands have developed from originally rather nutrient-poor ecosystems into more eutrophic ones because of largescale and intensive over-fertilization of agricultural croplands (Grützmacher and Schulte-Eickholt 2017). The enriched nitrogen contents combined with less humus in the agricultural soils have a negative impact on the percolation and water flow rates from the water catchment areas towards the peatlands. At the same time, precipitation rates are decreasing which puts the adequate water supply for peatland development at risk. Additionally, current conifer forests are less efficient with the accumulation of ground water compared to former broadleaved forest. Lastly, the increased nitrogen contents in the ground water and raising mean temperature leads to higher turnover rates of organic biomass which impedes the development of peat (Succow and Jeschke 2022).

## Forest growth assessments

Growth is a basic process of all natural organisms. In forests it applies as the increase of dimensions (diameter, basal area or height) of forest vegetation and the single tree compartments (roots, stem, branches, leaves and needles). Forest growth is a dynamic process influenced by various factors, including climate, soil quality, species composition, management practices and stand age. Effective management requires an understanding of forest growth, the factors influencing its development and the maximum sustainable yield that can be extracted. Forest growth assessments are therefore essential measures to determine its health and the productivity per area and time unit for forest management (Kramer and Akça 2002). Hereby, different terms indicate different measures which should be clearly separated.

Forest increment refers to the increase in dimension of one individual or a group of trees over a given period of time (Gadow 2003). Commonly, it is expressed as an annual increment. The mean annual volume increment is defined as the sum of several annual increments divided by the number of years (van Laar and Akça 2007). Forest yield furthermore indicates the final dimensions at a certain age of the forest stand. It is therefore used as a measure to determine the optimal harvest moment and the maximum harvestable quantity accumulative increment (expressed in biomass volume or mass per area unit) to be extracted in a sustainable manner.

Tree species-specific growth and yield information are listed in yield tables. These tables are based on extensive empirical data samplings of tree volumes and single tree growth modelling (Albert et al. 2021) and are developed for pure monocultures of particular tree species separated by site, forest management intensity and stand density. Yield classes are stating the harvestable biomass volume per unit area (usually 1 hectare), the mean tree height or mean diameter at the age 100. The yield class of a forest stand is determined by the relationship between forest stand age and its average growth parameters (tree height, breast-height-diameter or stand coarse wood volume per hectare).

## Forest Structure

The structure of forests refers to its physical organization, encompassing the vertical and horizontal distribution of vegetation, the dimension and age of trees and the presence of distinct forest layers. Forest structure shapes the conditional environment, including light availability, air and soil temperature and moisture content, which in turn affects the composition of species within the forest by providing niches for special-needs species. The layers of a forest, from the towering canopy to the diverse understory and the forest floor, each provide unique microhabitats that cater to different plant and animal species. Forest structure, therefore, plays a pivotal role in determining the abundance, distribution, and interactions of these species. Sabatini et al. (2015) and Storch et al. (2018) collected a variety of useful aspects of forest structure which have a direct impact on biodiversity, forest services and functions and its future development.

Forests are ecosystems based on high-growing trees. The tree heights as their main unique attribute compared to other ecosystems is a first important aspect of forest structure. The vertical heterogeneity caused by a broader range of tree heights within a forest stand may result from a higher variety of tree ages as they usually do not appear within even-aged plantation forests. Thus, it can be an indicator for highly structured and uneven-aged old-growth or close-to-nature forest management (Burrascano et al. 2013) which developed multiple layers of forest canopy. Natural resources such as light or precipitation are distributed differently to the single vegetation layers (Matsuo et al. 2022). Subsequently, a higher variety of forest strata can provide diverse environments and conditions (e.g. wind protection, cover or food) for special plant and animal organisms’ needs (Keeton 2006; Martins et al. 2017). Furthermore, the ability to establish an understory layer and ground vegetation within forest is adding other unique niches for potential forest specialists (Hao et al. 2007; Hatanaka et al. 2011).

Many studies consider a high species richness, specifically of broadleaved tree species, as an important measure to increase a forests structural diversity (Juchheim et al. 2019). Compositional species diversity though, does not only describe the richness in plant taxa which can stand in competition for nutrients, water and light but also supplementary compositions of species to either build symbiotic relationships or to complement functional gaps within the ecosystem. The mixture of opposite species couples such as shade-tolerant and light-demanding, shallow and deep-rooting or conifer and broadleaved species can optimize the spatial utilization of stocked area and niches, the proper distribution of scarce resources and the resilience of the entire forest ecosystem. Additionally, various physical and chemical attributes like light-transmittance of the canopy or litter quality are highly depending on the combination of tree species (Barbier et al. 2008). Besides serving as a seed source to the future forest regeneration, the choice of tree species composition also determines the appearance of ground vegetation and understory (Barbier et al. 2008; Barbier et al. 2009; Burrascano et al. 2011).

Accumulated biomass is another forest structural factor which affects the performance of ecosystem services, biodiversity and forest stability. High growing stocks contain lots of stored carbon sequestrated from the atmosphere (Hoover et al. 2012; Houghton 2005; Gilhen-Baker et al. 2022) and water to keep up the more humid microclimate with moderate temperatures (Norris et al. 2012) which also supports the ecosystem to face the disturbances and climate change (Ali and Wang 2021). This particularly applies to forests with a high proportion of old trees with larger diameters as they store water and carbon more efficiently (Stephenson et al. 2014). Furthermore, large trees are very valuable as micro-habitats because they provide a vast variety of species niches (e.g. tree caves, rough bark or dead wood compartments) for fungi, lichen, insects and smaller vertebrates (Bütler et al. 2013). All these effects can be well-observed in old-growth forest compared to secondary forests since they usually are able to outcompete even major secondary-growth forests in both high biomass stocks and the abundance of large-living trees (Hoover et al. 2012; Brunialti et al. 2010).

Lastly, deadwood biomass in the forest also displays a structural indicator for forest functionality and diversity. Just like their living counterparts, standing dead trunks and snags provide diverse habitat niches and food for rare species such as saproxylic fungi and insect species (Persiani et al. 2010; Lassauce et al. 2011) but also many mammals and birds are using hollow or piled up woody structures for shelter. While coarse woody debris of any kind is important, big standing logs are playing a special role due to their long existence and slow decomposition rate compared to smaller pieces lying on the forest ground (Gärtner et al. 2023). Besides the biodiversity aspects, deadwood is a key element within ecosystem cycles and processes. The additional biomass stores water and serves as a cooling factor for its environment. Through its decomposition, the nutrients which were taken up by the former tree and are now stored in its biomass, can be recycled back into the ecosystem to become available for new tree growth and hence enriches the quality of the site (Prescott 2002; Weis et al. 2016). In general, dead wood accumulation is an indicator for close-to-nature conditions within a forest (Castagneri et al. 2010) since intensively managed forest are often fully cleared of woody biomass because of wildfire fuel reduction but also economic purposes (Weis et al. 2016). Thus, managed forests had no chance to accumulate dead wood on a higher scale. This especially becomes visible when deadwood decay classes are missing within a forest stand. The absence of certain classes usually indicates the extraction of deadwood which leads to a disturbance in the continuous addition of new deadwood and the succession of decomposition (Lombardi et al. 2011).

# Methods

## Study area

Since being conducted as a part of the Peatland Monitoring Program for Climate Protection – Forest (German: Moorbodenmonitoring für den Klimaschutz - Wald [MoMoK-Wald]), this study is based on the data obtained from the 50 defined monitoring sites of the MoMoK-Wald project. By the time of writing this master thesis (until October 2023), the data collection has taken place on 34 of these monitoring sites (Fig. 1), thus, only the results of this limited number of plots are part of the scope and can be considered in the analysis of this study.

The monitoring sites are distributed across Germany throughout the federal states of Schleswig-Holstein (n = 2), Lower Saxony (n = 6), Mecklenburg-Western Pomerania (n = 4), North Rhine Westphalia (n = 1), Saxony Anhalt (n = 1), Brandenburg (n = 6), Rhineland-Palatinate (n = 2), Hesse (n = 3), Thuringia (n = 2), Saxony (n = 4), Baden-Württemberg (n = 1) and Bavaria (n = 2). Each site is then categorized by its peatland type, the forest stand’s main tree species and the hydrological status of the peatland. The peatland types are divided into bogs (n = 10), fens (n = 21) and gley bogs or fens (n = 3). Transition bogs are treated as normal bogs. For the MoMoK-Wald project only peatland sites are selected which indicate a homogenous forest stand (main tree species share of > 80 %) and the main tree species being European black alder (*Alnus glutinosa [L.] GAERTN.* [n = 13]), Downy birch (*Betula pubescens EHRH.* [n = 7]), Norway spruce (*Picea abies [L.] H. KARST.* [n = 8]) or Mountain pine (*Pinus mugo TURRA* [n = 6*]*). The hydrological status is differentiated between drained (n = 19) and normal (n = 15) peatlands. The drained sites also include peatlands which are partially drained and the normal sites summarize all peatlands which are either close to nature (non-drained), very slightly drained or even rewetted.

A map of germany with different colored dots

Description automatically generated

Fig. 1 – Map showing the of monitoring sites all over Germany. The Map was created in QGIS (QGIS Development Team 2023) using open source data from (2022) and (2019)

## Plot and study design

The plot design and data sampling methodology are based on the sampling and analysis manual for the MoMoK-Wald project.

On each monitoring site, a 0.25 ha square sampling plot with a side length of 50.00 m is installed in reference to a previously defined GPS point. From this reference point, the plot’s center point and all 4 plot corners of the sampling plot are placed as boundaries and described by their polar coordinates. The plot’s center point and corners are marked with wooden sticks for visual identification. The sampling plot consists of several single sub-plots to assess the different parameters of interest.

A verbal forest stand description is conducted throughout the entire square sampling plot (Fig. 2). In a circular plot with a radius of r = 12.62 m around the main plot center, every tree and its growth and vitality parameters are recorded. Additionally, standing and downed deadwood is sampled and measured within the same circular plot. The location of the main plot center is selected in a way that the heterogeneity of the site is optimally represented by the sample plot. For the regeneration survey, 4 circular satellite plots are established with a distance of 10 m in all 4 main geographic directions from the main plot center. Each of the satellite plots has a radius of r = 5.00 m around their plot center. Additionally, a vegetation survey is conducted on 4 randomly distributed 100 m2 (Σ 400 m2) sub-plots within a 30 m radius around the main plot center.

A diagram of a plot

Description automatically generated

Fig. 2 – Plot design: Squared sampling plot (edge length: 50.00 m) with a circular forest inventory plot (radius: 12.62 m) and 4 satellite circular plots for the natural regeneration survey (radius: 5.00 m)

## Data sampling

The polar coordinates are derived from distance and azimuth measurements between the plot center point and the plot corners or satellite points by using a Vertex device (Haglöf 2023) and a compass.

For all trees within the main circular plot (A = 500.34 m2) and which are classified as merchantable wood and thus, have a breast height diameter DBH ≥ 7 cm, the growth and vitality parameters are recorded. This includes the identification of tree species, the polar coordinates in relation to the center point, the measurement of the DBH with a girth tape and an estimation of the Kraft’s class for all trees. The tree height and crown base height are only measured for a minimum of 5 trees per site but covering all occurring DBH classes. It was measured by using a Vertex device. Lastly, the tree or forest stand age is derived from various sources (Tab. 1).

Tab. 1 – Age determination (Wellbrock et al. 2022)

|  |  |  |
| --- | --- | --- |
| Code | Type | Method |
| 1 | FE | forest inventory |
| 2 | whorl | counting of branch whorls (only conifers) |
| 3 | tree stumps | counting of growth rings on tree stumps |
| 4 | growth rings | counting of growth rings on borer cores |
| 5 | estimation | estimation |
| 6 | PC | preliminary clarification by forestry companies |

The deadwood survey is carried out on the main circular plot (A = 500.34 m2) as well. The measurements of the deadwood’s length or diameter are done according to its classification (Tab. 2) and only when the minimum criteria for a deadwood type is met. Here all parts of the deadwood pieces are included which are lying within the 12.62 m radius, even when its origin was rooted outside of the circle. Outlying parts of included pieces are cut off.

For downed deadwood (1), length of the trunk or branch and its center diameter (diameter at the half of its length) is measured. Standing dead trees (2) and snags (3) are recorded by their DBH and the height of their trunk. When measuring tree stumps (4), the height of the stump and the average diameter at the cutting surface (aDSC) need to be assessed. For completely downed trees (5) the length of the trunk is measured as well as the DBH. In the case of deadwood, which was piled up (6), the average center diameter of the single pieces is determined and their length is estimated. In the end, the degree of decay (Tab. 3) must be determined for all deadwood pieces.

Tab. 2 – Deadwood types (Wellbrock et al. 2022)

|  |  |  |
| --- | --- | --- |
| Code | Deadwood type | Criteria |
| 1 | downed deadwood, branches, twigs, crowns | diameter ≥ 10 cm at the thicker end |
| 2 | standing tree | DBH ≥ 10 cm, with branches |
| 3 | snag | DBH ≥ 10 cm, height ≥ 13 dm, without branches |
| 4 | stump | aDCS ≥ 10 cm, height < 13 dm |
| 5 | downed tree | DBH ≥ 10 cm |
| 6 | piled deadwood | diameter ≥ 10 cm at the thicker end |

Tab. 3 – Degree of decay (Wellbrock et al. 2022)

|  |  |
| --- | --- |
| Code | Degree of decay |
| 1 | no decay |
| 2 | solid wood, 10 % altered wood structure, low infestation of wood-decomposing organisms, no limbs < 3 cm |
| 3 | slight decay, 10-25 % altered wood structure, easy insertion with a sharp tool |
| 4 | medium decay, 26-75 % of the wood is soft to very soft; or friable, original cross section of the wood might have altered |
| 5 | strong decay, 76-100% of the wood is soft, original cross section of the wood has altered |

The regeneration survey is conducted in 4 circular sub-plots (A = 78.54 m2) located at the satellite points around the main plot center. Here, the 10 trees which are closest to the sub-plot center point are recorded but not further than 5 m away from the center. Only those trees are considered in the survey which exceed the minimum height of 2 dm but are not part of the forest inventory (DBH < 7 cm). If there are more than 10 trees within the given radius, the distance of the 10th farthest tree is measured as well as the height of all recorded trees. Furthermore, the tree species is identified.

In the vegetation survey, an estimated degree of ground cover is recorded for every plant species separated by forest strata (Tab. 4) and subplot. The obtained data is then merged for one total vegetation plot of 400 m2 by building the mean value of the ground cover degree for all plots.

Tab. 4 – forest strata (Wellbrock et al. 2022)

|  |  |
| --- | --- |
| Strata | Description |
| Tree 1 | all wooden and climbing plant species of the main stand |
| Tree 2 | all wooden and climbing plant species above 5.0 m height but not being part of the dominating main stand |
| Shrub | all wooden and climbing plant species (≥ 0.5 m and < 5.0 m height) |
| Herb | all grass and herbal plant species without height limitation as well as wooden and climbing plant species below 0.5 m height |
| Moss | all epigeic and epilithic moss and lichen species |

Tab. 5 lists up the measurement equipment and its usage for the data collection as well as the software used for data analysis.

Tab. 5 – Measurement tools and analysis software

|  |  |  |  |
| --- | --- | --- | --- |
| Tool | Usage | Resolution | Precision error |
| Haglöf Vertex V\* | distances | 0.01 m | ± 0.0001 m (1 %) |
| height (by distance and 2 angles) | 0.1 m | ± 0.001 m (1 %) |
| compass | azimuth | 1.0 gon | ± 0.01 gon (1 %) |
| girth tape | breast height diameter | 0.1 cm | ± 0.001 cm (1 %) |
| measuring tape | length of downed deadwood | 0.1 cm | ± 0.001 cm (1 %) |
| tree caliper | diameter deadwood | 0.1 cm | ± 0.001 cm (1 %) |
| meter stick | height of tree stools and natural regeneration | 0.1 cm | ± 0.001 cm (1 %) |
| Quantum GIS V.3.30.3 | GIS and mapping |  |  |
| RStudio V. 2023.06.0 | statistics and plotting |  |  |

\* source: Haglöf 2023

## Calculations

### Biomass volume

The biomass volume of a tree is highly related to its diameter and height, thus, the volume is commonly calculated through different volume functions using one or even both variables as an input. To estimate the biomass volume per hectare, it usually only requires the basal area of the sample plot and the average tree height which is representative for the entire forest stand. A more precise approach is to collect the information about the DBH and the height of every single tree on the plot that has been recorded during the data sampling process and then calculating the volume of each single tree. Afterwards the accumulated biomass of the entire sample plot can be extrapolated for the area of one hectare. Since only the heights of 5 to 10 trees, covering all DBH classes, have been sampled according to the methodology, the missing height must be estimated.

For the estimation of the missing tree heights hp, a self-fitted non-linear least squares (NLS) model is conducted by using the relation between DBH and tree height in the equation 1 (Braga et al. 2023b)

|  |  |
| --- | --- |
|  | 1 |

and the forestmangr::nls\_table command (Braga et al. 2023a) to predict the fitting parameters b0 to b2. The NLS model is applied separately for each species and plot when there are at least 3 height measurements per tree species and plot available. Furthermore, the coefficient of determination R2 for the NLS model must exceed a value of 0.7 in order to ensure a sufficient fitting of the model prediction to the entry data. In case, there are less than 3 heights measured for a tree species on a plot or if the R2 value is lower than 0.7, the NLS model is fitted for the heights of each tree species but throughout all plots together.

When there are less than 3 tree heights measured per tree species on all plots together or the R2 value remains below 0.7, the height curve of SLOBODA (Sloboda et al. 1993) is used and hp is calculated with following equation

|  |  |
| --- | --- |
|  | 2 |

with dg being the diameter and hg the height of the mean basal area tree and k0 and k1 being species related curve-fitting coefficients (Tab. 6). Birch and alder trees are assigned to the group of other short-living broadleaved trees (SLB) according to the third National Forest Inventory (Riedel et al. 2017).

Tab. 6 – species related curve-fitting coefficients for SLOBODA height curves (Dahm 2006)

|  |  |  |
| --- | --- | --- |
| Tree species group | k0 | k1 |
| Spruce | 0.183 | 5.688 |
| Fir | 0.079 | 3.992 |
| Douglas fir | 0.240 | 6.033 |
| Pine | 0.290 | 1.607 |
| Larch | 0.074 | 3.692 |
| Beech | 0.032 | 6.040 |
| Oak | 0.102 | 3.387 |
| LLB\* | 0.122 | 5.040 |
| SLB\*\* | 0.032 | 4.240 |

\* LLB = long-living broadleaved trees  
\*\* SLB = short-living broadleaved trees

But if there is no information on the required parameters for the height curve of SLOBODA available, the more abstract and less precise approach of CURTIS (Curtis 1967) is used. The function for this height curve (equation 3) only requires information about the DBH of the tree to predict its height.

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with b0 to b2 being the fitting coefficients for the CURTIS height curve as stated in Tab. 7. Here all non-listed conifer species are treated as spruce and all non-listed broadleaved species as beech trees (e.g. alder and birch).

Tab. 7 – Species related curve fitting coefficients for CURTIS height curves

|  |  |  |  |
| --- | --- | --- | --- |
| Tree species group | b0 | b1 | b2 |
| Spruce | 434.1235 | -65,586.6915 | 3,074,967.1738 |
| Beech | 382.0202 | -51,800.9382 | 2,374,368.3254 |
| Fir | 453.5538 | -81,132.5221 | 4,285,801.5636 |
| Pine | 359.7162 | -42,967.9947 | 1,763,359.9972 |
| Larch | 421.4473 | -60,241.2948 | 2,895,409.6245 |
| Douglas fir | 481.5531 | -81,754.2523 | 4,193,121.2406 |
| Oak | 348.3262 | -46,547.3645 | 2,119,420.9444 |

#### Vonderach and Huber

The trees’ biomass volume is then estimated by the biomass function from Vonderach

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with b0 – 15 being coefficients (Tab. 8) to estimate the biomass of the coarse wood of the tree without its bark (b0 – 3), the bark of the coarse wood (b4 – 7), the foliage of only the conifer tree species (b8 – 11) and the fine branches and their bark (b12 – 15). The biomass is then given in kilograms.

Tab. 8 – Species related coefficients for the VONDERACH biomass function

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Coef. | Spruce | Fir | Douglas fir | Pine | Beech | Oak | Ash | Maple |
| b0 | 0 | 0 | 0 | 0 | -5.6602 | -5.9489 | 0 | 0 |
| b1 | 0.0157 | 0.0074 | 0.0128 | 0.0169 | 0.0220 | 0.0257 | 0.0128 | 0.0280 |
| b2 | 1.7350 | 1.6476 | 1.9541 | 1.9894 | 2.0971 | 2.0738 | 1.9623 | 2.1304 |
| b3 | 1.2177 | 1.5543 | 1.0539 | 0.9378 | 0.8957 | 0.8508 | 1.1824 | 0.7078 |
| b4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5195 |
| b5 | 0.0042 | 0.0017 | 0.0027 | 0.0044 | 0.0017 | 0.0060 | 0.0010 | 0.0040 |
| b6 | 1.6026 | 1.3040 | 1.8296 | 1.9594 | 2.0245 | 2.0101 | 1.0000 | 2.0680 |
| b7 | 1.0239 | 1.8956 | 1.0032 | 0.6641 | 0.9396 | 0.7780 | 1.6592 | 0.6965 |
| b8 | -2.6807 | 0 | -2.3439 | 0 | 0 | 0 | 0 | 0 |
| b9 | 0.4639 | 0.0961 | 0.3042 | 0.0967 | 0 | 0 | 0 | 0 |
| b10 | 2.806 | 1.7136 | 2.4415 | 2.3781 | 0 | 0 | 0 | 0 |
| b11 | -0.9393 | 0 | -1.2707 | -1.1093 | 0 | 0 | 0 | 0 |
| b12 | 0 | 0 | 0 | 0 | -5.6602 | -5.9489 | 0 | 0 |
| b13 | 0.0157 | 0.074 | 0.0128 | 0.0169 | 0.0220 | 0.0257 | 0.0128 | 0.0280 |
| b14 | 1.7250 | 1.6476 | 1.9541 | 1.9894 | 2.0971 | 2.0738 | 1.9623 | 2.1304 |
| b15 | 1.2177 | 1.5543 | 1.0539 | 0.9378 | 0.8957 | 0.8508 | 1.1824 | 0.7078 |

Since the function of Vonderach starts with negative values or 0, the calculation of the biomass volume for trees with a low height and a narrow DBH value is not valid anymore and creates negative results. For these trees, the biomass is then estimated by an adaptation of Huber’s formular:

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with BA being the basal area of the tree and SC being 0.5 as a simplified version of a coefficient to describe the bole shape of the tree. Afterwards the volumes are converted into masses (unit: kilogram) to be comparable to the biomass results estimated with the Vonderach function. Therefore, the tree volumes are multiplied by species-related estimations of tree compartments (Tab. 9), the density of each tree species (Tab. 10) and a wood density correction factor for branches depending on the type of wood (conifers = 1.3444; diffuse-porous = 1.0961; ring-porous = 1.0611).

Tab. 9 – Estimated percentage share of each tree compartment (in %)

|  |  |  |  |
| --- | --- | --- | --- |
| Tree species group | Coarse wood and bark | Branches | Foliage\* |
| Spruce | 0.679 | 0.167 (+ 0.094) | 0.094 |
| Pine | 0.709 | 0.180 (+ 0.049) | 0.049 |
| Beech | 0.763 | 0.175 | 0 |
| Oak | 0.689 | 0.188 | 0 |

\* coefficient for foliage only for conifer trees

Tab. 10 – Wood density

|  |  |
| --- | --- |
| Tree species group | Density |
| Spruce | 0.3788 |
| Fir | 0.3629 |
| Douglas fir | 0.4141 |
| Pine | 0.4307 |
| Larch | 0.4873 |
| Poplar | 0.3538 |
| Beech | 0.5583 |
| Oak | 0.5707 |
| Maple | 0.5222 |
| Alder | 0.4283 |
| LLB | 0.5642 |
| SLB | 0.4618 |

Subsequently, the single tree biomass values are summed up for each plot. Afterwards, the total plot biomass is extrapolated for a total area of one hectare.

#### TapeS

Kublin, E., J. Breidenbach and G. Kaendler (2013). “A flexible stem taper and volume prediction method based on mixed-effects B-spline regression.” European Journal of forest research 132(5-6): 983-997.

Vonderach, C., G. Kändler and C. F. Dormann (2018). “Consistent set of additive biomass functions for eight tree species in Germany fit by nonlinear seemingly unrelated regression.” Annals of Forest Science 75(2): 49.

Tree biomass is estimated through biomass functions from the German National Forest Inventoy. The above-ground biomass (AGB) function by Kändler and Bosch (2013) is divided into 3 parts. AGB of trees with a DBH ≥ 10 cm is derived from:

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with D03 being the diameter of the tree trunk at 30 % of the tree’s height and b0–3 and k1,2 being species related coefficients (Tab. 11).

Tab. 11 – Species related coefficients for the above-ground biomass function of trees with a DBH ≥ 10 cm

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Tree species group | b0 | b1 | b2 | b3 | k1 | k2 |
| Spruce | 0.75285 | 2.84985 | 6.03036 | 0.62188 | 42.0 | 24.0 |
| Pine | 0.33778 | 2.84055 | 6.34964 | 0.62755 | 18.0 | 23.0 |
| Beech | 0.16787 | 6.25452 | 6.64745 | 0.80745 | 11.0 | 18.8 |
| Oak | 0.09428 | 10.26998 | 8.13894 | 0.55845 | 400.0 | 12.1 |
| SLB | 0.27278 | 4.19240 | 5.96298 | 0.81031 | 13.7 | 50.0 |

AGB of large trees with a DBH above a certain species-related threshold value (spruce ≥ 69 cm; pine ≥ 59 cm; beech ≥ 86 cm; oak ≥ 94 cm; SLB ≥ 113 cm) are calculated by

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with Bs being the biomass at the species-related threshold diameter DBHs, the species-related parameters D03s (Eq. 8) and Hs (Eq. 9) at DBHs and the species-related coefficients b0,s,3, c0,1, a and b (Tab. 12).

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For trees with a diameter at breast height of < 10 cm but with a tree height h ≥ 1.3 m the above-ground biomass function

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is used with Ds being 10 cm as the maximal diameter within the validation limit of this biomass function and b0,s, 3 being species related coefficients (Tab. 12).

Tab. 12 – Species related coefficients for the above-ground biomass function of trees with a DBH < 10 cm and a height ≥ 1.3 m

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Tree species group | b0 | bs | b3 | c0 | c1 | a | b |
| Spruce | 0.41080 | 26.63122 | 0.0136956 | 1.07843 | 0.91204 | 0.27407 | 2.22031 |
| Pine | 0.41080 | 19.99943 | 0.0091576 | 0.89009 | 0.95747 | 0.29722 | 1.98688 |
| Beech | 0.09644 | 33.22328 | 0.0116212 | 0.84014 | 0.98970 | 0.29397 | 1.76894 |
| Oak | 0.09644 | 28.94782 | 0.0150089 | 0.87633 | 0.98279 | 0.31567 | 1.63335 |
| SLB | 0.09644 | 16.86101 | -0.0055086 | 0.86720 | 0.96154 | 0.28064 | 2.40288 |

The AGB of trees with a height < 1.3 m is estimated by following equation

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with tree height as dependent parameter and b0 and b1 as species related coefficients (Tab. 13).

Tab. 13 – Species related coefficients for the above-ground biomass function of trees with a height < 1.3 m

|  |  |  |
| --- | --- | --- |
| Tree group | b0 | b1 |
| Conifer trees | 0.23059 | 0.04940 |
| Broadleaved trees | 2.20101 | 2.54946 |

The below-ground biomass BGB is calculated with the same biomass function (Eq. 12) as the AGB for trees with a height below 1.3 m but with DBH as the dependent variable and the species-related coefficients b0 and b1 which are listed in Tab. 14

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Tab. 14 – Species related coefficients for the below-ground biomass functions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Tree species group | b0 | bs | parameter | source |
| Spruce | 0.003720 | 2.792465 | DBH [cm] | Bolte et al. 2003 |
| Pine | 0.006089 | 2.739073 | DBH [cm] | Neubauer and Demant 2016 |
| Beech | 0.018256 | 2.321997 | DBH [cm] | Bolte et al. 2003 |
| Oak | 0.028000 | 2.440000 | DBH [cm] | Drexhage and Colin 2001 |
| SLB | 0.000010 | 2.529000 | DBH [mm] | Johansson and Hjelm 2012 |

Subsequently, the individual tree biomass values (AGB + BGB) are summed up for each plot. Afterwards, the total plot biomass is extrapolated for a total area of one hectare.

#### Own attempt

The individual trees’ biomass is estimated with species-related biomass functions collected by Zianis et al. (2005). For the calculations in this study, the biomass functions with the highest ranked R2 estimations are selected for each tree species (Tab. 15).

Subsequently, the single tree biomass values are summed up for each plot. Afterwards, the total plot biomass is extrapolated for a total area of one hectare.

Tab. 15 – Biomass functions and coefficients a-c for various tree species (Zianis et al. 2005)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Tree species | Equation | a | b | c | R2 | source |
| Alder |  | 0.0841 | 2.4501 |  | 0.991 | (Hughes 1971) |
| Beech |  | -2.872 | 2.095 | 0.678 | 0.997 | (Hochbichler 2002) |
| Birch |  | -1.6047 | 0.9450 |  | 0.994 | (Mälkönen and Saarsalmi 1982) |
| Douglas fir |  | -2.535 | 2.009 | 0.709 | 0.998 | (Bartelink 1996) |
| Fir |  | 5.2193\*10-4 | 1.459 |  |  | (Broadmeadow and Matthews 2004) |
| Larch |  | 0.00564 | 3.041\*10-5 | 2.1058 |  | (Broadmeadow and Matthews 2004) |
| Maple |  | -2.7018 | 2.5751 |  | 0.995 | (Bunce 1968) |
| Oak |  | -1.56 | 2.44 |  | 0.940 | (Drexhage and Colin 2001) |
| Pine |  | 22.63177 | -6.7506 | 49 | 0.999 | (Brække 1986) |
| Poplar |  | 5.75\*10-4 | 1.873298 |  | 0.959 | (Johansson 1999) |
| Spruce |  | -43.13 | 2.25 | 0.452 | 0.995 | (Fiedler 1986) |

### Forest yield classes

The calculation of forest yield classes is a measure to evaluate the forest stand productivity in consideration of its site and growth conditions (Gadow 2003). The forest increment analysis is only applied to the main tree species (alder, birch, pine or spruce) of each plot. For the assessment of the yield class the height of the mean basal area tree (Hg) in relation to the age of the forest stand is used.

Once all tree heights are measured or estimated, the height of the base area mean trunk hg per plot, tree species and age class is calculated by a function of Schnell, S. ():

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From the hg and age of the forest stand, the yield class is determined visually by inserting them into the plotted yield tables of Alnus glutinosa (Lockow 1994), Betula pubescens (Lockow 1996a), Pinus sylvestris (Lembcke et al. 1975) and the yield table of Wiedemann (1936) for moderately-intensive management for Picea abies by (1995). Since downy birch trees rarely appear purely but are often crossed with sandy birch, the data of Betula pubescens is compared to the yield table of Betula pendula (Lockow 1996b) as well.

### Forest structural indices

A forest’s structure can be described by various quantitative and qualitative measures. (2018) developed a methodology to combine 11 variables of forest structure and summarize them in one Forest Structure Index (FSI). In this study, the methodology is used by applying 9 of the 11 forest structure variables which were possible to be obtained from the data sampling. For the FSI, the calculations have been applied to all occurring trees on the sampling plot without the separation of species or the limitation to the main tree species of the plot.

From the DBH, two variable indices have been derived. The quadratic mean of tree diameters at breast height DBHq shall identify the growing stock and its increment. The root mean square (Eq. 14) of the measured diameters is used because it represents the true stand diameter more accurately than the arithmetic mean diameter (Curtis and Marshall 2000).

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The standard deviation of the diameters DBHsd gives an estimation of the uneven-agedness of the forest stand by the distribution of different diameter classes. The vertical heterogeneity of the forest plot is described by the standard deviation of heights of trees which have a DBH ≥ 7 cm. From the DBH and tree height h of trees with a DBH ≥ 40 cm, the volume of trees Vol40 is calculated with the tree volume equation from (1828) (Eq.  15) and later extrapolated to an area of 1 hectare.

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with A being the basal area of the tree and SF being a correction factor (here 0.5) for the bole shape. With this variable index the biomass volume of large, living trees is estimated.

Various indices are developed from the samplings of the deadwood survey. The amount of deadwood comprises 2 indices by determining the mean diameter of both standing (type 2 and 3) DWs and downed deadwood (types 1, 4, 5 and 6) DWd separately. A third index estimates the variety of decay levels by counting the different decay classes which are occurring on each plot.

Species richness is considered for another 2 variables. The number of tree species (DBH ≥ 7 cm) per plot SR is taken both from the stand inventory and the vegetation survey (from the strata Tree 1 and Tree 2) separately to estimate the compositional heterogeneity of the forest. Furthermore, the number of tree species in the regeneration strata SRreg is derived from the regeneration survey and the vegetation survey (all wooden species from the Shrub and Herb strata) as a measure for the species diversity in the regeneration layer. Later the indices obtained from the forest inventory / regeneration survey are compared to the ones from the vegetation survey during the data analysis.

The index for each variable VIi is calculated by Eq. 16. The index then takes a value between 0 and 1, which indicates the structural diversity of a plot in relation to all other considered plots.

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with X being the calculated variable value of the sampling plot, Xmax being the highest and Xmin being the lowest value of this variable from the entire data set. The FSI equals the average of all variable indices and is described by Eq. 17 (Storch et al. 2023)

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with n being the number of applied variables.

## Statistics and analysis

All calculations and statistics have been carried out with R (R Core Team 2023) in RStudio (RStudio Team 2023) and are then plotted by using the packages “ggplot2” (Wickham 2016), “patchwork” (Pedersen 2023) and “RColorBrewer” (Neuwirth 2022) for visualization.

First of all, both the forest growth and the Forest Structure Index are analyzed by descriptive statistics. For forest growth, a paired t-test or alternatively a non-parametric Welch-test is applied, when the database is too small or not normally distributed to compare the birch data with the yield classes of *Betula pubescens* and *B. pendula*. The same methodology is applied to the results of the forest structure analysis to compare the SR and SRreg indices for the obtained data from the forest inventory / regeneration survey with the results of the vegetation survey.

Later statistical tests are applied to compare the different plots and forest types for significant differences due to their different ecological characteristics, e.g. the main tree species, the peatland type, the hydrological conditions and soil related criteria.

Statistical tests to compare sites and forest types

* ANOVA + Tukey (posthoc) or Kruskal Wallis test + pairwise wilcox test (holm) (posthoc)
* Linear Mixed Effect Models