Carbon storage in alpine mires: A case study from Platzertal (Austria)

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SUMMARY

Alpine peatlands play a crucial role in mountain watershed functions and services while supporting high biodiversity. Their reliance on cool and humid conditions makes them particularly vulnerable to climate change, including rising temperatures and decreasing precipitation, as well as human disturbance. Moreover, their carbon storage potential must be integrated into global climate models. However, alpine peatlands remain largely unrecorded, and their typically thin or absent peat layers leave their role as carbon reservoirs unclear. This study investigated carbon stocks in Platzertal, an alpine valley at 2,300 metres above sea level in the Ötztal Alps, Tyrol, Austria. The area features numerous small-sedge swamps spanning 7.11 hectares. The study site was divided into 143 sub-sites with an average area of 497 m². Peat volume, bulk density, dry weight and total organic carbon were analysed in 40 samples from these sub-sites. To achieve a comprehensive understanding of peat layer depth across the area, 666 plots were established to classify soil types and measure peat layers. The average peat layer depth was 11 cm, ranging from 5 to 100 cm. The carbon stock of the study area was calculated using the carbon density approach. The total area (7.11 hectares) of small-sedge swamp has a peat volume of 6,223 m³ and stores approximately 282 tons of carbon, equivalent to 1,036 tons of CO_2 in total or approximately 146 tons of CO_2 per hectare. These figures are significantly lower than those reported for other peatland regions, particularly the extensive boreal peatlands of the Northern Hemisphere. Our findings highlight that, whilst alpine peatlands have significant ecological importance and offer various ecosystem services, their contribution as soil carbon reservoirs is comparatively minor.

KEY WORDS: carbon sequestration, peat density, peat layer depth, peatlands, total carbon

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INTRODUCTION

Peat is a soft sediment with a high content of fibrous material which has accumulated under conditions of waterlogging, nutrient and oxygen deficiency and high acidity (IPS 2021). Its organic matter content is at least 65 % (Salimin *et al*. 2010). Peatland ecosystems are characterised by a partially decomposed peat layer more than 30 cm thick. The formation of peat and the atmospheric carbon sink function of peatlands are the result of excess plant production compared to respiratory losses through decomposition (Moore & Knowles 1989, Diessel 1992). With their unique vegetation composition, natural peatlands are valuable habitats in terms of biodiversity, are nutrient sinks, and play an important role in water cycling and carbon sequestration. Because of their unique functions and requirements for cool and moist conditions, they are highly sensitive to human disturbance and climatic changes (Tarnocai & Stolbovoy 2006, Minayeva & Sirin 2012, Leng *et al.* 2019, Antala *et al.* 2022). Throughout the Holocene, which started approximately 10,000 years ago, peatlands have been accumulating large amounts of organic carbon (Roulet *et al.* 2007, Yu 2012) and have been playing an important role in the global carbon cycle (Yu 2012). Although they account for less than 3 % of the global terrestrial area (approximately 3.4 × 106 km^2, based on data from the Global Peatland Database/Greifswald Mire Centre, accessed in July 2024), northern peatlands in the boreal and subarctic regions store one-third of the global soil carbon (455 Pg C) (Gorham 1991). This makes it essential to include them in the modelling and analysis of global C cycling to mitigate changes in other carbon reservoirs (Brovkin *et al.* 2002, Kleinen *et al.* 2010, Menviel & Joos 2012). Due to their role in carbon sequestration and net cooling effects on the global radiation balance, peatlands are essential in maintaining the global climate (Dise

2009). Large-scale peatland degradation by drainage for agriculture, forestry or peat extraction can result in considerable emissions of carbon dioxide (CO_2) and other greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) (Whiting & Chanton 1992, Reeburgh *et al*. 1998, Kløve *et al*. 2010, Hatala *et al*. 2012, Ojanen *et al*. 2013, Laine *et al*. 2019, Mozafari *et al*. 2023). Therefore, although peatlands are generally recognised as a net sink for CO_2, depending on the water regime, they are also a major source of methane (CH_4), with estimated annual emissions of 177–284 Tg CH_4, making them the most significant non-anthropogenic CH_4 source (Vroom *et al.* 2022). Especially in alpine regions, with a highly patchy landscape pattern and considerable variations in length of growing season, vegetation cover, water regime and climatic properties, the carbon fluxes show high variability (Bowman & Fisk 2001).

Although the largest peatland areas are found in boreal regions, peatlands are also numerous across tropical, temperate and boreal mountain areas because of the higher annual precipitation, cooler temperatures and higher levels of available water compared to the conditions in the surrounding lowlands (Cooper *et al.* 2012). Alpine peatlands occur in alpine, sub-alpine and mountainous regions across several continents but are particularly prominent in the European Alps, on the Tibetan Plateau and in the Andes, with smaller peatland areas in high-elevation areas in Russia (especially Siberia), North America and Oceania (Assiri *et al.* 2022). Their distribution is largely influenced by elevation, climate and the presence of glacially carved landscapes that support peat formation (Wunderlich *et al.* 2023). However, in alpine locations, the classic soil science-based definition of peatlands falls short. At higher elevations, typical swamp communities of the class "small-sedge swamps and moors" (Scheuchzerio-Caricetea fuscae) can be formed. According to other authors (Mucina *et al.* 1993), these communities are widespread throughout the Northern Hemisphere and often form moderately to weakly productive stands in raised and quaking bogs. Such areas are characterised by a thin or even absent peat layer (Wittmann *et al.* 2007), mainly because of the considerable disturbance regime, the oxygen-rich soil water and low plant productivity resulting from the low temperatures and a short vegetation period (Koch 2007, Liebner *et al.* 2011). Although a minimum peat depth of 30 cm is used for the assessment of global inventories of peatlands, there is no minimum peat depth for a site to be classified as a peatland (Joosten & Clarke 2002, Craft 2016). This is particularly the case for alpine peatlands, where the peat layer may be relatively thin because of rocks deposited by rockslides or avalanche events (Woodhurst & De Scally 2017). Alpine mires (bogs and fens) differ substantially from sub-(arctic) wetlands in terms of light regime, the lack of permafrost and the presence of an insulating snow cover (Franchini *et al.* 2014) during the cold season, but they have similar life zones and plant communities (Körner 1999). Alpine mires provide valuable catchment functions and services such as runoff regulation (Buytaert *et al.* 2006, Spieles 2022), the provision of habitat for rare and endangered species (Hauer *et al.* 2007), riparian area stabilisation (Grab & Deschamps 2004) and the regulation of greenhouse gas emissions. To provide these services (Millar *et al.* 2023, Balode *et al.* 2024), specific hydrological conditions are required, with a long-term water balance that promotes near-surface soil saturation during part or all of the growing season (Mitsch & Gosselink 2000).

In the context of the current debate on climate change, studies on the carbon balance and stocks of terrestrial ecosystems are important because any changes in the global climate are expected to facilitate positive feedback mechanisms (Schlesinger & Andrews 2000). Alpine environments, which are adapted to cold temperatures, are expected to respond highly sensitively to global temperature increases. In this sense, the protection and restoration of peatlands play an important role in climate change mitigation (Parish *et al.* 2008). The role of alpine mires in the global carbon cycle is largely unclear. In contrast to northern wetlands, alpine habitats have been little studied regarding their carbon stocks and fluxes.

To precisely determine the soil organic carbon stocks of peat soils, also with regard to potential mitigation measures, the accurate assessment of bulk density (BD) is crucial (Dettmann *et al.* 2022). Commonly, BD is determined by measuring the oven-dry weight of a volume-based sample. Given the specific properties of peat soils, which are characterised by a loose, spongy structure and, in some cases, even consist of a living root mat (van Asselen *et al.* 2018), volume-based sampling is complicated. According to the international standard DIN EN ISO (2001), the sampling method of choice uses steel cylinders (sampling rings) to obtain an intact peat soil column with a defined volume. An advantage of this method is that the height of the cylinder does not exceed the diameter, thereby minimising the effect of disturbed soil interfacing the cylinder wall (Blake & Hartge 2018).

The European Alps contain numerous small peatland areas, which are largely threatened by rising temperatures and decreasing precipitation levels (Pullens *et al.* 2016). In Austria, more than 90 % of the original peatland area has been degraded by drainage to generate land for agriculture and forestry, and the remaining peatlands are often located at higher elevations. However, these alpine peatlands are largely unrecorded. Currently, there are more than 1,300 peatlands in the country, individually covering areas mostly below 1 ha and rarely exceeding 10 ha, and mainly located on slopes (Krisai 1998). Although this largely precludes a precise area calculation, other authors report a total peatland area of 24,000 ha for Austria (Paternoster *et al.* 2021).

Platzertal, an alpine valley at 2,300 m above sea level, is located in the Ötztal Alps, Tyrol (Austria) and characterised by numerous small-scale swamps which formed approximately 10,000 years ago at the end of the last glacial period. Related to the planned expansion of the Kaunertal hydropower plant, which would affect approximately 7 ha of this alpine peatland area by removal of the H horizon (the layer rich in partially decomposed organic material that is typical for peatlands) and subsequent impounding, we determined the carbon storage of this alpine mire complex. Our investigations are based on measurements of the carbon stock of small-sedge swamp soils and the thickness of the peat horizons. Using soil maps of all affected small-sedge swamp areas in Platzertal, we assessed the importance of the region as a carbon reservoir. It should be highlighted that, despite the potential role of alpine fens as CH_4 and CO_2 sources, for simplicity, we focused on the carbon density of the soils in our study site and on the soil C stocks, which we determined using the carbon density approach (Yu 2012).

Alpine mires, with their specific characteristics, are under-represented in the literature, especially regarding their carbon sequestration ability. The overall aim of this study is to determine their role as carbon reservoirs, and we address the following research question: what is the amount of stored carbon in the alpine mire area in Platzertal?

METHODS

Study area

The study site is a 7.11-ha alpine fen area in the Ötztal Alps. The high valley, at an elevation of 2,300 m above sea level (Figure 1), is traversed by a main stream with several side arms. It is situated above the tree line and has near-natural vegetation consisting of a mosaic of grassland patches and dwarf shrubs. The climate is cold temperate (Köppen classification Dfb), with mean annual temperature -1.8 ºC and mean annual precipitation 1,248 mm (https://chelsa-climate.org/climate-diagrams/. The area is characterised by typical plant communities for nutrient-poor fens and swamps belonging to the class "small-sedge swamps and fens" (Scheuchzerio-Caricetea fuscae). The dominant plant species are *Carex nigra*, *C. paupercula*, *C. echinata*, *Eriophorum scheuchzeri* and *E. angustifolium*, along with *Juncus filiformis*, *Trichophorum cespitosum* and *Epilobium nutans*. In terms of peat-forming plants, species of the peatmoss genus *Sphagnum* such as *S. compactum*, *S. quinquefarium*, *S. rubellum* and *S. subnitens* are present, along with various *Carex* species. There are no drainage ditches or fertilisation regimes in place. However, the area is subject to non-intensive cattle grazing for about two months during the summer. In this study, all areas recorded as "swamps" in the various data sets obtained via vegetation or habitat mapping are referred to as "swamp areas". The most important habitat types summarised under this term are raised, transitional and quaking bogs, fens, bog forests, large- and small-sedge fens and reed beds.

Mapping and soil sampling

The entire terrain was mapped in June 2022 and 2023 in terms of peat layer depth and vegetation. For the entire Platzertal study area, the thickness of the peat layer, encompassing the different soil types, was determined (Egger & Kucher 2023). Since the small-sedge swamp communities of the fens in Platzertal are discrete (not connected) areas that differ in terms of their plant communities and peat layer depths, they were partitioned into a total of 143 sub-sites, each with a unique identification number (area ID). Sub-site sizes ranged from 16 to 2,589 m^2, with an average of 497 m^2. For each sub-site, we determined the soil type by visual inspection and the finger test, which is a simple and practical method to assess soil texture based on feel and appearance (Thien 1979). On this basis, we characterised the soil types encountered as peat (high content of largely undecomposed fibrous organic matter), peat-moor (mixture of peat and moor soil which contains both undecomposed and decomposed organic matter and is found mainly in the transition area between peatlands and other ecosystems) or moor-silt (with a significant presence of silt particles along with organic matter).

In addition, we established 666 plots across the study area for measurement of peat layer depth. For all medium- to large-sized sub-sites, we obtained one or two (from the centre and the edge) depth measurements using a Pürckhauer soil auger. This way, all larger sites were sampled several times and the entire study area was represented. Across all sub-sites, we randomly took 40 (942.48 cm^3) soil samples for measurement of BD, pH, dry weight and soil

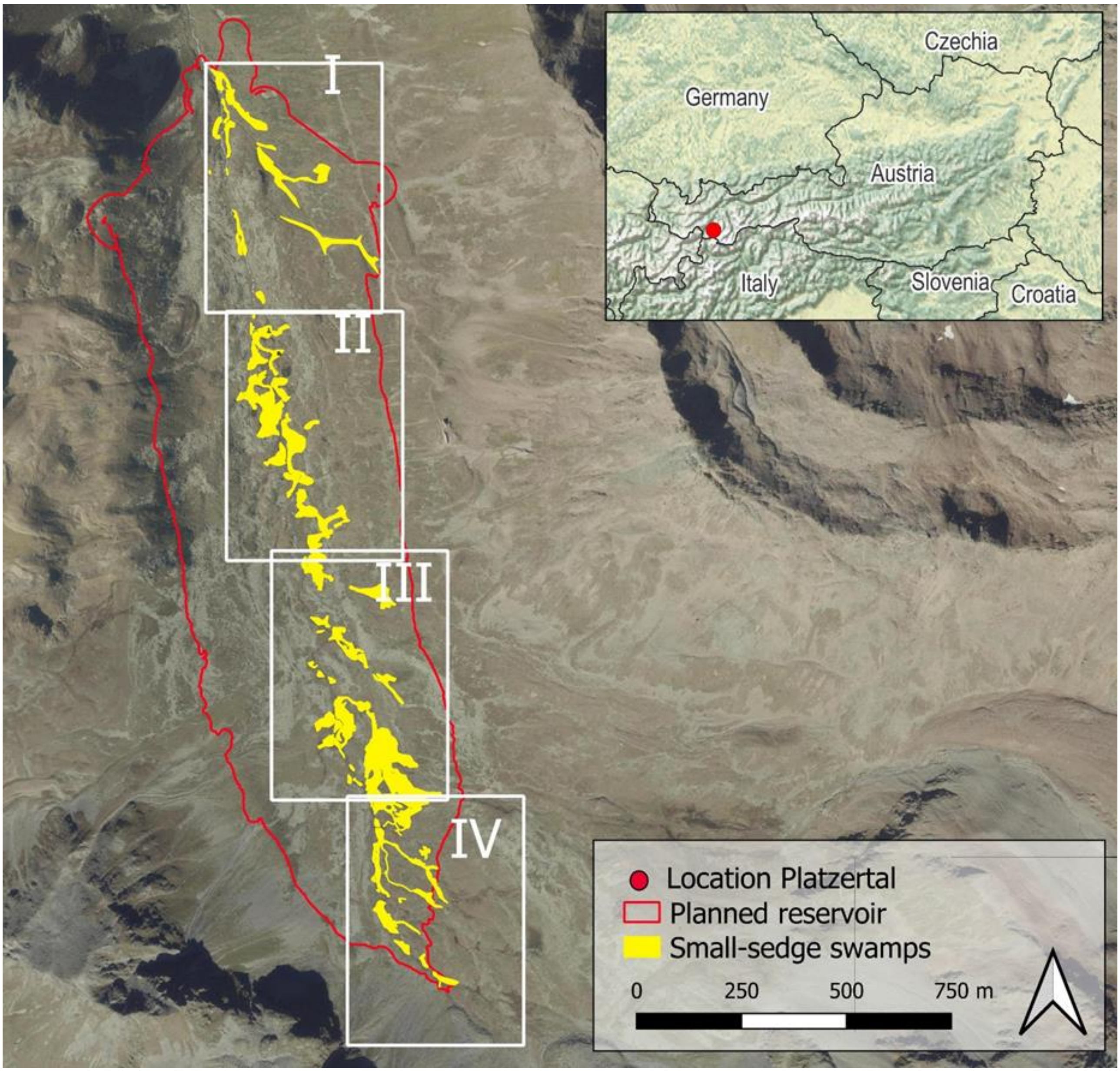

Figure 1. Overview of the study area Platzertal in Tyrol, Austria (Sections I to IV). Areas in yellow represent the small-sedge swamps. The red border outlines the planned reservoir (sources: basemap.at, TIWAG).

organic carbon (SOC) from the 5–10-cm subsoil layer using a steel cylinder. Soil samples were taken in June 2023 (for SOC determination) and October 2024 (for the determination of soil moisture, BD and pH). The same sub-sites were sampled in both years. For sampling, we gently removed the top 5-cm layer and dug out a small hole to a depth of 10 cm to expose the soil. We then pressed the sharp edge of the cylinder vertically into the soil to a depth of 10 cm perpendicular to the ground and carefully removed it to extract the intact soil core. At three sites, we collected additional soil cores from the 20–30-cm, 40–50-cm and 70–80-cm layers, depending on the thickness of the peat layer. For this, we dug a hole to the required depth and removed the intact soil core with the cylinder, as described above. The collected soil cores were placed in plastic bags, transported to the laboratory and stored at 4 °C until analysis. Figure 2 shows the distribution of the 143 sub-sites and sampling plots across the study area.

Calculation of peat volumes for the 143 sub-sites

Using the 666 depth measurements and inverse distance weighted interpolation (IDW) with a distance coefficient P of 4 and a pixel size of 0.1 m (QGIS), we determined the peat layer depths across the entire study area (Figure 3, left side). Based on the obtained grid data (resolution 0.1 m) and the areas

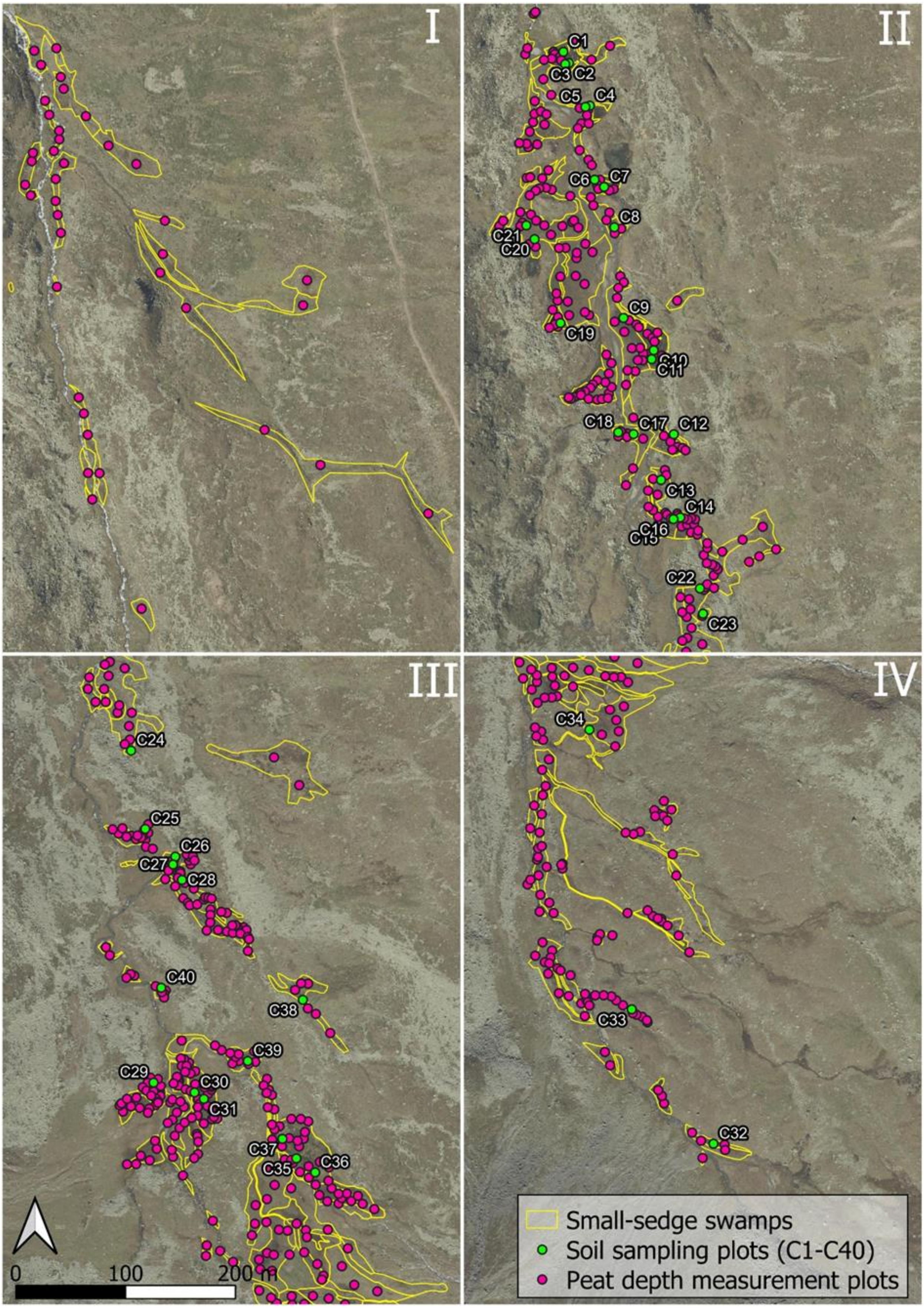

Figure 2. Distribution of sub-sites (n = 143; yellow outlines), peat depth measurement plots (n = 666; pink dots) and soil sampling plots (C1 to C40; green dots) across the study area (Sections I to IV, see Figure 1).

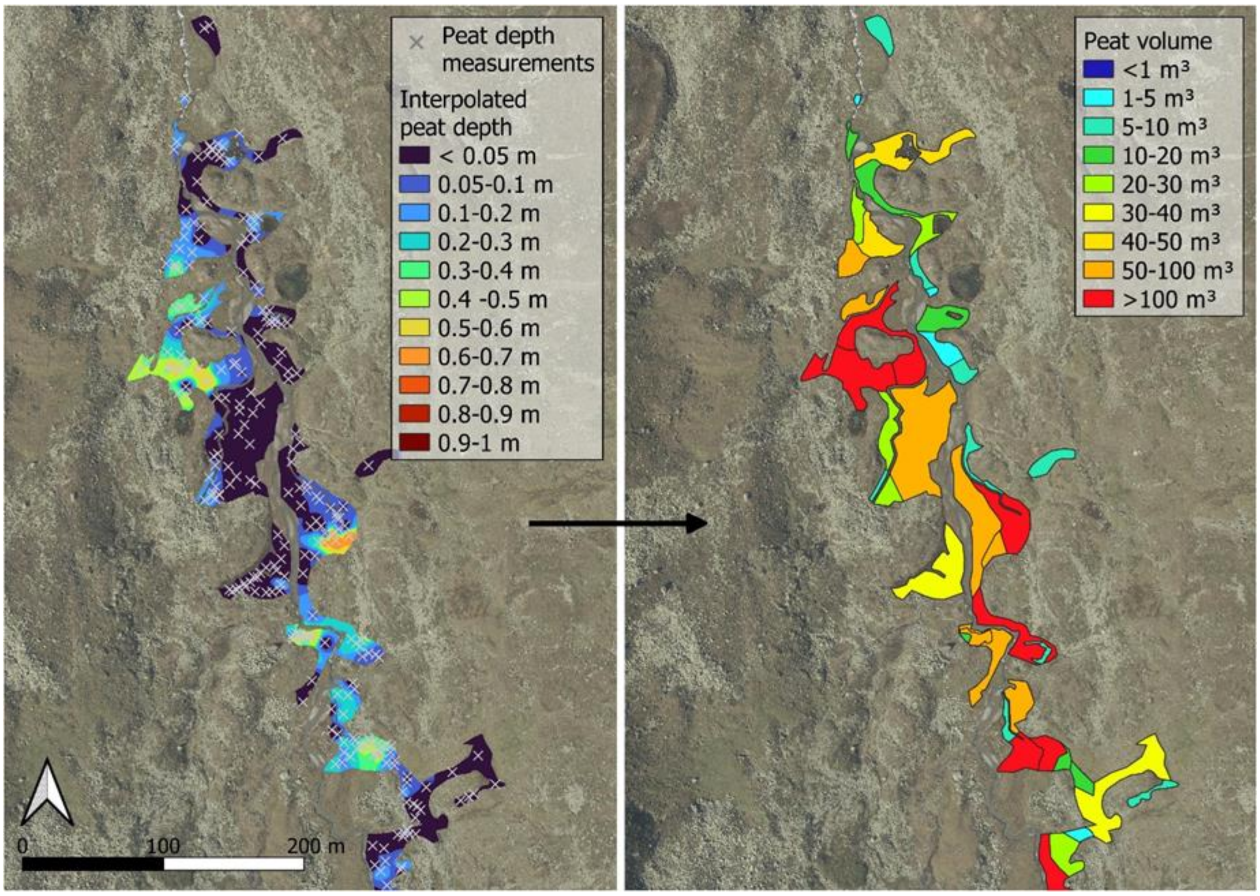

Figure 3. Interpolated peat depths (left) and calculated peat volume values for Section II sub-sites (C1–C23).

of the 143 sub-sites, we determined the peat volume (m^3) (Figure 3; right side) using the QGIS Volume Calculation tool.

Determination of soil properties

Prior to analysis, each sample was manually homogenised in the plastic bag. Soil pH was determined in a 1:5 soil : water slurry using a pH electrode (PeakTech 5310 A). Soil moisture was determined gravimetrically by oven-drying 50–100 g of soil at 105 °C for 24 h. The dry weight was calculated based on soil moisture loss, and dry BD (g cm^{-3}) was determined as (dry weight (g) ÷ field volume (cm^3)). For the sampled sub-sites, the BD values calculated from the soil samples were used. If more than one soil sample was taken within a sub-site, the average was calculated. In the sub-sites for which no soil samples were taken, the average BD values for their soil types were used. The average value for the moor-silt soils was calculated from the 21 samples characterised as moor-silt; the average value for the peat-moor soils was calculated from the nine samples characterised as peat-moor; and the average value for the peat soils was calculated from the ten samples characterised as peat.

For all 40 soil samples, the SOC concentration was determined chromatographically according to the standard ÖNORM L 1080 (1987) at the Institut für Lebensmitteluntersuchung, Veterinärmedizin und Umwelt des Landes Kärnten. When more than one soil sample was taken within one sub-site, the average was determined. For the sub-sites that were not sampled, the SOC values based on the respective soil type were used (Figure 4). The average SOC values for moor-silt, peat-moor and peat soils were calculated using the values of the respective 21, 9 and 10 samples.

Calculation of C and CO_2 stocks for the small-sedge swamp soils

The C stock of the small-sedge swamp soils (i…sub-site (n = 143)) was calculated from the soil volume V_i (cm^3), BD_i (g cm^{-3}) and SOC_i (%), using the following equation (adapted from Yu 2012):

$$C = \sum_i (V_i \times BD_i \times SOC_i) \quad [1]$$

Based on the BD values calculated for the different depths, we observed no significant increase in BD with depth.

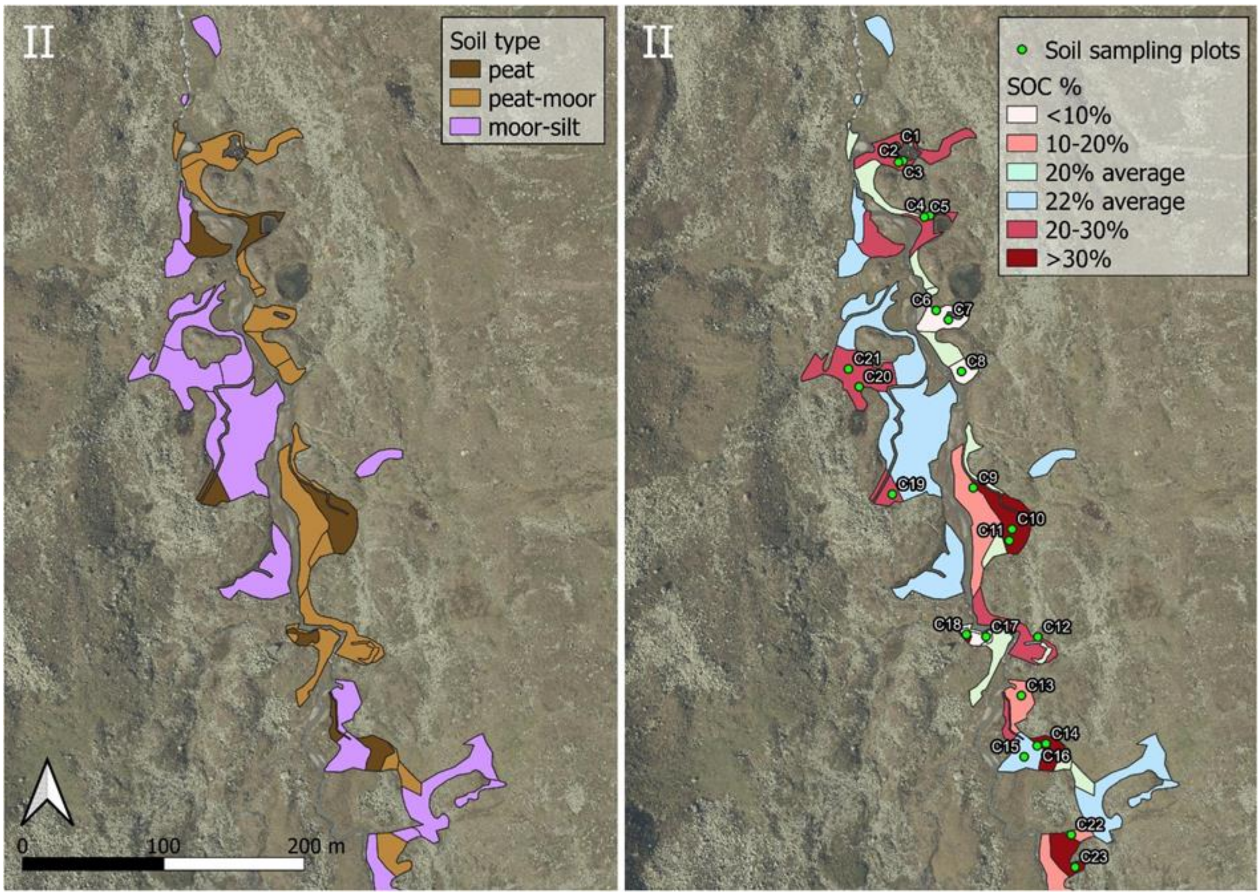

Figure 4. Distribution of the sub-sites (n = 143) depending on the soil type (left) and distribution of the soil sampling plots (C1–C23) in relation to the SOC (soil organic carbon, %) content (right), for Section II.

Carbon fluxes are strongly dependent on seasonality. As seasonal changes were not accounted for in this study, due to the climatic characteristics of the study area, we only calculated the theoretical CO_2 stock, which was obtained by converting the C into CO_2 (based on the molecular weights of C and O, where 1 kg of C is equivalent to 3.667 kg of CO_2).

RESULTS

Soil pH, bulk density, peat layer depth, and peat volume

Across all sites, soil pH ranged from 4.65 to 6.29, with an average of 5.74. This indicates that the presence of carbonates can be excluded, and total C is equivalent to organic C. Overall, the BD values ranged from 0.06 to 0.39 g cm^{-3}, with an average of 0.20 g cm^{-3}. There were no significant changes in BD with depth. The measured depth of the peat layer (666 plots) ranged from 0.005 to slightly above 1.0 m, with an average of 0.11 m (Figure 5). For 585 measurement plots (87.84 %), the depth was below or equal to 0.3 m. Depths above 0.3 m were measured at 81 plots (12.16 %).

Regarding the different soil types, for peat, the BD values ranged from 0.2 to 0.58 g cm^{-3}, with an average of 0.34 g cm^{-3}. In the peat-moor sites, the range of BD was from 0.06 to 0.74 g cm^{-3}, with an average of 0.3 g cm^{-3}. The moor-silt sites showed a BD range of 0.08 to 0.58 g cm^{-3}, with an average of 0.21 g cm^{-3} (Figure 6).

Figure 7 shows the interpolated peat depths of all small-sedge swamp areas across the study site.

The small-sedge swamps in Platzertal cover an area of 7.11 ha, with a total peat volume of 6,223 m^3 (0.4–203.6 m^3, as calculated based on the peat depth values of the 143 sub-sites). This results in an average moor or peat layer of 0.087 m. Figure 8 shows the peat volume levels for all 143 sub-sites.

Carbon stock

The peat sites had SOC levels from 4.67 % to 43.77 % of dry soil weight, with an average of 19.84 %. For the peat-moor sites, we determined SOC levels from 4.67 % to 43.77 % of dry soil weight, with an average

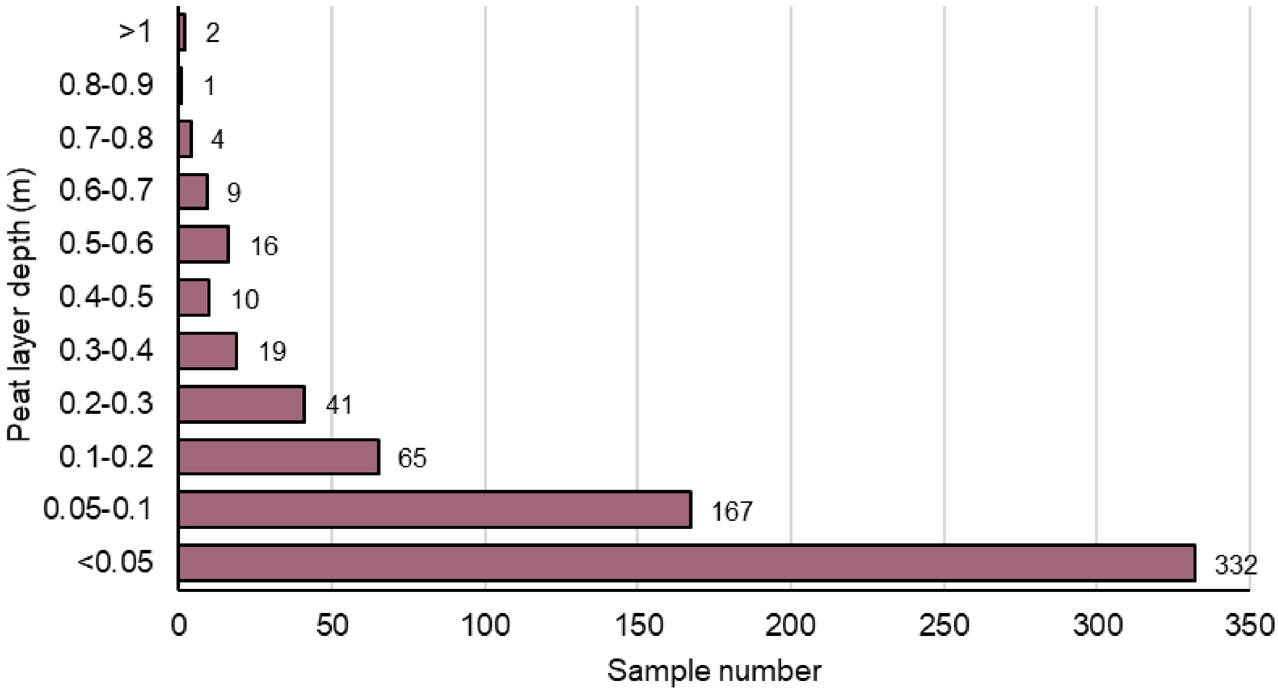

Figure 5. Peat layer depth values for the 666 sampling plots.

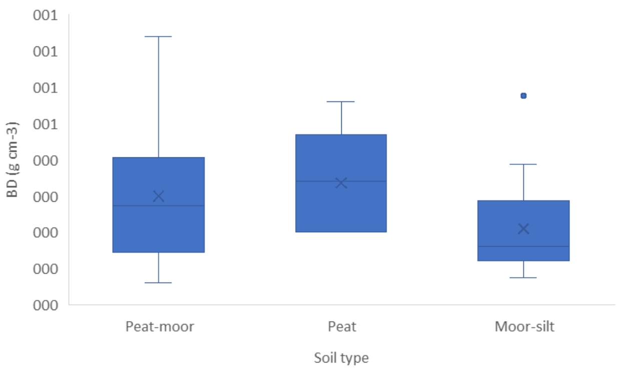

Figure 6. Box and whisker plot showing the variation in bulk density (g cm^{-3}).

of 20.86 %. For the moor-silt sites, the SOC levels ranged from 5.51 % to 43.77 % of dry soil weight, with an average of 20.29 % (Figure 9). Accordingly, the 7.11-ha small-sedge swamp, with a peat volume of 6,223 m^3, stores approximately 282.49 tons of carbon. Using the calculation from Yu (2012), the stored CO_2 amounts to 1,036 tons, with approximately 146 tons (Mg) per hectare (Table 1, Figure 10).

Across all sampling sites, the BD and SOC were weakly negatively correlated, with an r^2 value of 0.08 (Figure 11), suggesting that only approximately 8 % of the variance in the SOC can be explained by the BD.

DISCUSSION

Whilst there is a large body of literature on the carbon stocks and dynamics of subarctic and tropical peatlands, alpine peatlands - such as alpine mires and fens - have largely been neglected in this regard. In the European Alps, in contrast to the vast boreal peatland areas, there are numerous small mires and fens, often with different vegetation communities, making overall estimations challenging (Pullens *et al*. 2016).

More than half of the global wetlands are composed of peatlands (Osman 2018), and to determine the actual carbon sequestration potential of peat areas (bogs and fens), the peat layer thickness is of crucial importance. As organic soils may be present beneath vegetation types unrelated to peat formation conditions, the presence of peat cannot be reliably inferred from the vegetation cover. This is especially the case near the edges of peatlands, where the natural relationship between vegetation and the underlying peat layer may have been disturbed (Ivanovs *et al.* 2024). In this study, we therefore performed 666 depth measurements across all sampling plots and used inverse distance weighted (IDW) interpolation to determine peat depths across the entire study area. The values ranged from 5 to 100 cm, with most of the plots showing a peat depth below 30 cm. However, as mentioned above,

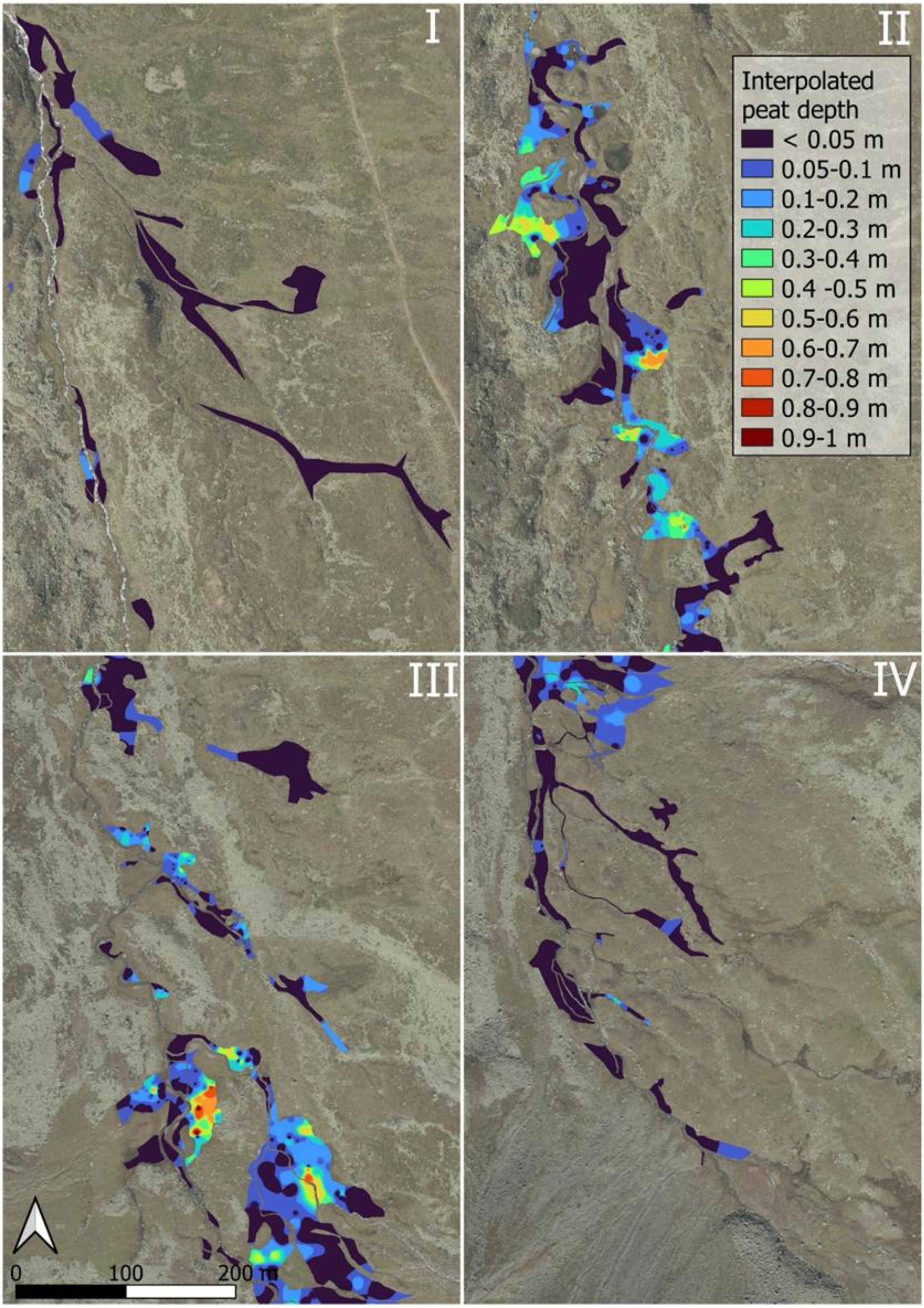

Figure 7. Interpolated peat depth values across the study site (Sections I to IV).

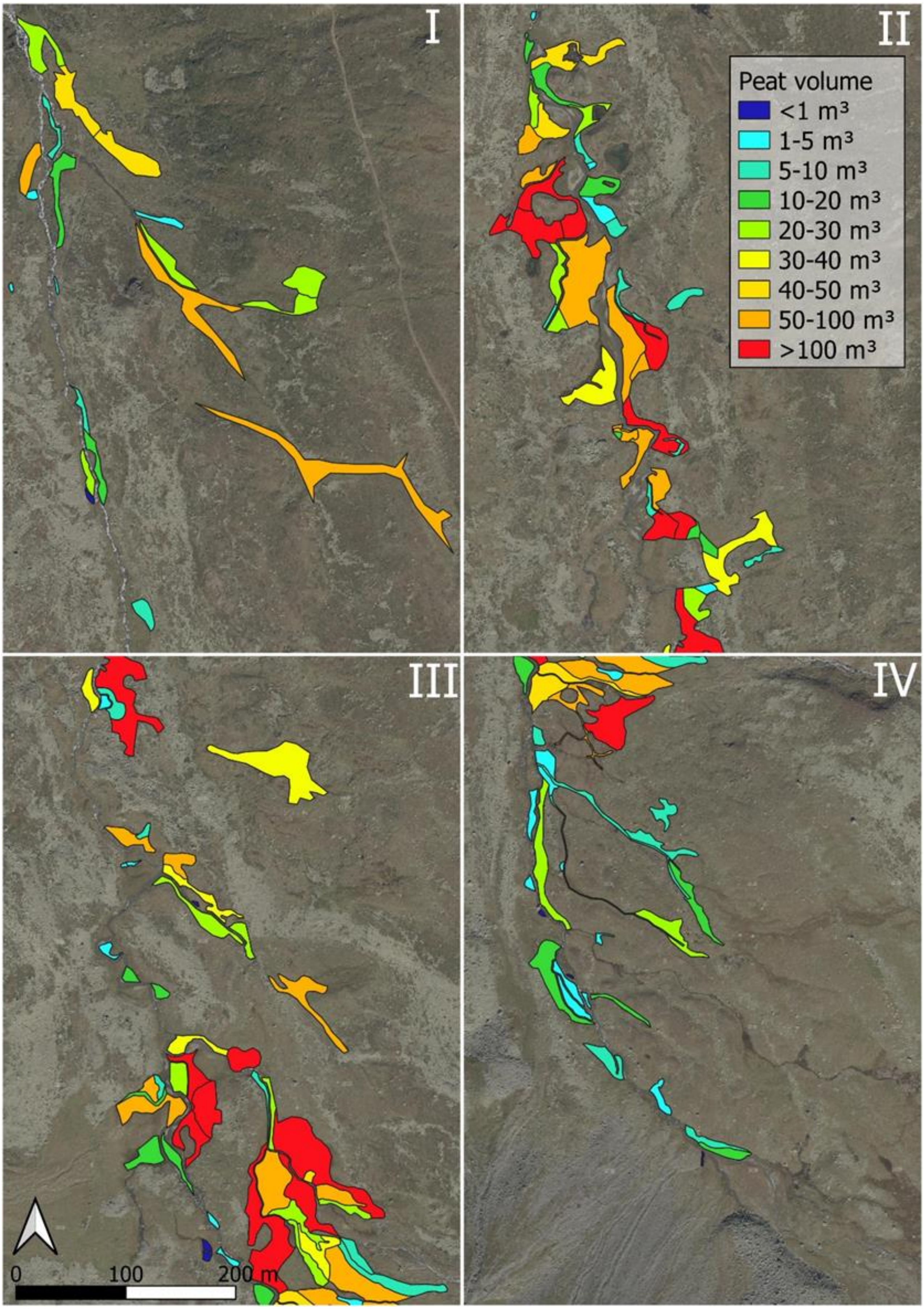

Figure 8. Calculated peat volume values across the study site (Sections I to IV).

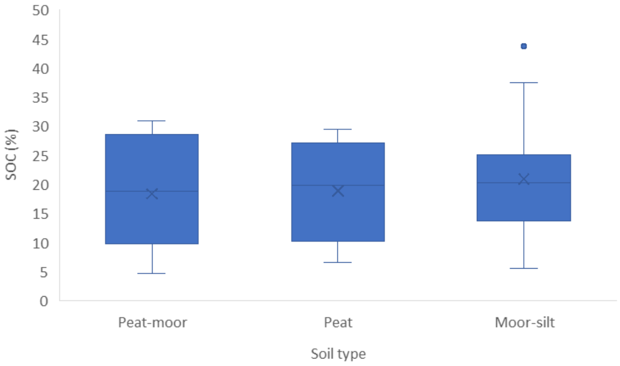

Figure 9. Box and whisker plot showing the variation in SOC (soil organic carbon, %) across the different soil types.

Table 1. Overview of the peat area, peat volume, and C and CO_2 stocks of the study area. The carbon stocks of the different sampling sites ranged from < 0.01 t to approximately 44 t. The carbon stock distribution is shown in Figure 10.

Total area	7.11 ha
Total peat volume	6,223 m^3
Total C stock	282 t
C stock per ha	40 t ha^{-1}
Total CO_2 stock	1.036 t
CO_2 stock per ha	146 t ha^{-1}

particularly in alpine peatlands, peat layer thickness may be extremely low (Woodhurst & De Scally 2017). The low peat depth values recorded in our study are in stark contrast to those obtained for two valley peat bogs in the eastern Austrian Alps, with values of up to 800 cm (Drollinger *et al.* 2020). The peat depths ranging from 20 to more than 600 cm reported from a study on the carbon stocks of alpine peatlands on the Qinghae Tibetan Plateau were also considerably higher than our values (Chen *et al.* 2014). The authors of a study in the Italian Alps reported a peat layer with a depth of up to 400 cm (Pullens *et al.* 2016). Andean alpine peatlands, which are common at elevations of 3,000 to 5,000 m throughout the South American tropics, have peat deposits up to 1,000 cm thick, with an average of 500 to 600 cm (Hribljan *et al.* 2024). A mean peat thickness of 280 cm has been reported for a mountain wetland in Peru (Monge-Salazar *et al.* 2022), and Sass *et al.* (2010) measured a peat layer thickness between 140 cm and more than 600 cm in a study on small alpine mires at elevations of 1,300 to 1,500 m in Tyrol (Austria).

High peat layer thickness values have also been reported for the vast northern peatlands of the boreal and subarctic regions. For example, according to the Estonian Soil Classification (ESC), the peat layer thickness of peaty soils is 10–30 cm, whereas that of shallow peat soils is 30–100 cm (Kõlli *et al.* 2016). The authors of a study on cultivated peat areas in the Dutch coastal plains reported a peat layer thickness of < 50 to 350 cm (van Asselen *et al.* 2018), whereas values of up to 1,200 cm have been observed in Norway (Paniagua *et al.* 2021). In Finland, peat layer thickness values of 10 to 400 cm have been measured (Tuittila *et al.* 2012). Mean peat depths ranging from approximately 190 to 260 cm for bogs and from 140 to 215 cm for fens have been reported from the Ontario Hudson Bay Lowlands (O´Reilley 2011). The Mackenzie River Basin of northern Canada (overlapping with part of continental western Canada), the second largest peatland complex in North America, has an overall peat layer depth of 220 cm (Vitt *et al.* 2005), whereas in West Siberia (the largest peatland basin in the world), peat layer depth is more than 200 cm (Sheng *et al.* 2004). This supports the assumption that peat accumulation in alpine areas is generally considerably slower than in boreal peatlands. According to Krisai (1998), for peatlands above an elevation of 1,700 m, erosion plays a significant role. For most of these areas, peat formation is inhibited; the peat layer is no longer growing but, rather, stagnating or even in the process of degradation, which is more likely to be a result of intensive grazing than of climatic changes (Krisai 1998). In our sites, the low peat layer depths can be explained by the lack of peat-forming vegetation, and livestock grazing during summer which largely prevents peat formation.

Dry BD is an accurate predictor of carbon density in peat soil (Crnobrna *et al.* 2022), which is in agreement with our findings. However, the SOC was very weakly negatively correlated with BD, with an r^2 value of 0.08. This indicates that BD is not a strong indicator of SOC in our sites. This might, at least partially, be a result of high microbial activity, which leads to the rapid turnover of organic matter and, consequently, higher SOC levels while not considerably altering BD. Whilst a negative correlation between BD and SOC has been reported for crop soils (e.g., Weil & Magdoff 2004, Mestdagh *et al.* 2006, Sakin 2012), information about this relationship in peat soils is scarce. Because of their loose structure, peatlands are characterised by low BD (Osman 2018). Their BD values are generally lower than those of mineral soils due to the lower

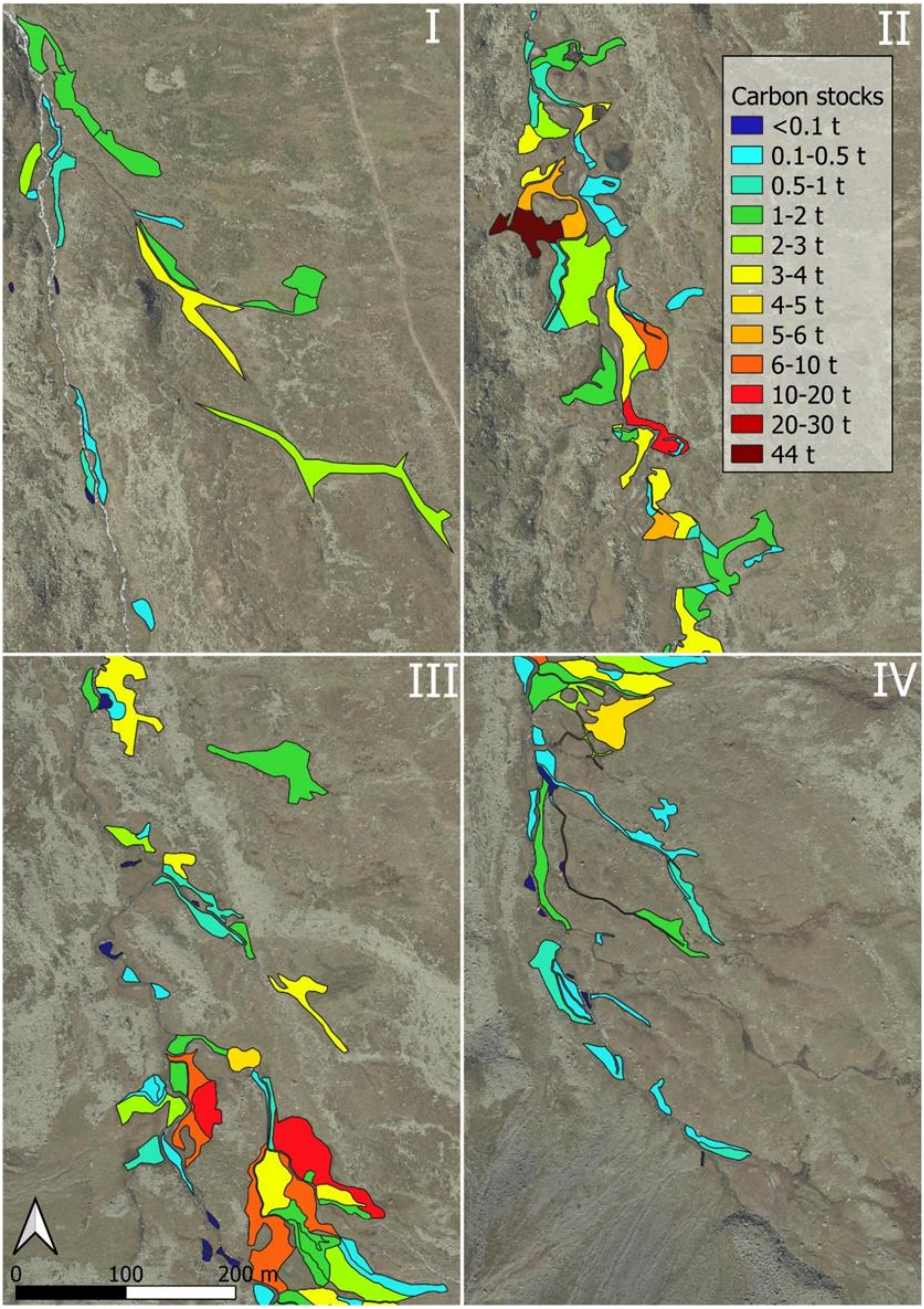

Figure 10. Carbon stock values (t) across the study site (Sections I to IV).

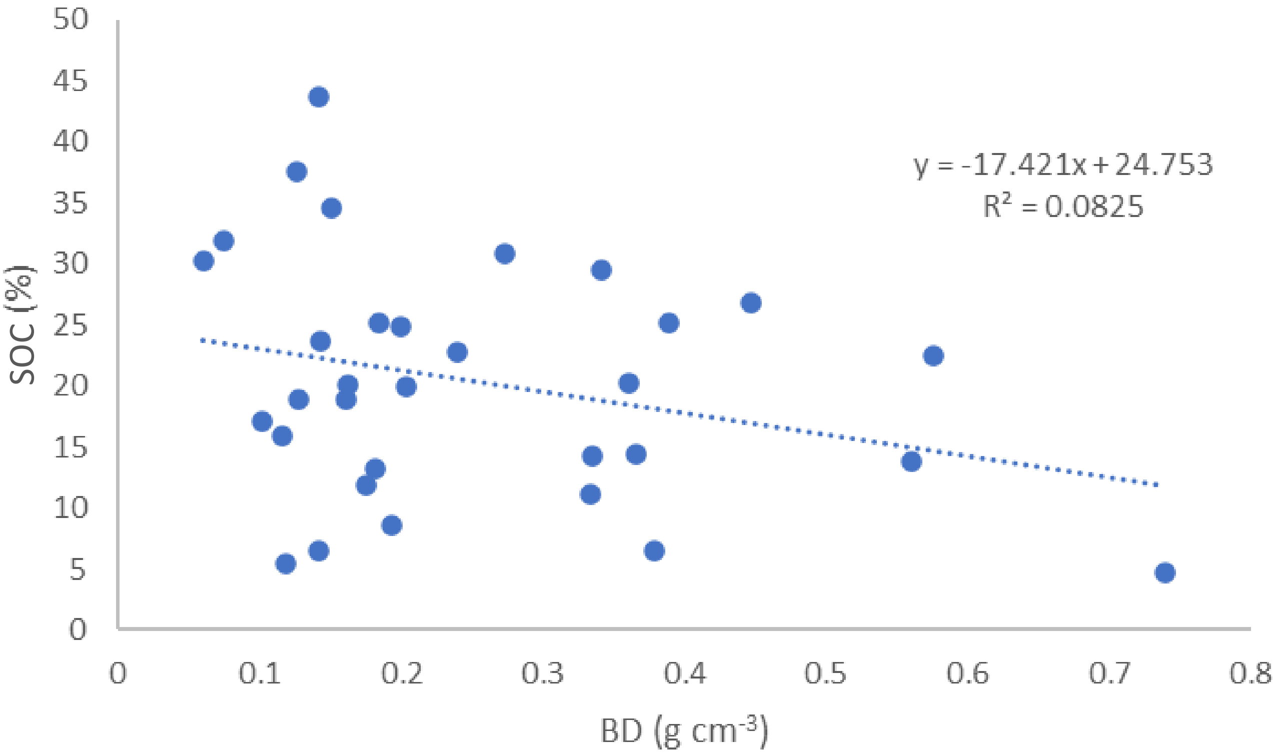

Figure 11. Scatterplot showing the correlation between SOC (soil organic carbon, %) and BD (bulk density, g cm^{-3}).

specific gravity of their solids and their higher water-holding capacity, along with the presence of gas (Huat *et al*. 2011).

Especially when recently formed, peat generally has a loose and heterogenous structure and contains various plant remains; in some cases, it consists of a living root mat with an extremely low BD (van Asselen *et al.* 2018). In the present study, the mean BD values at a depth of 5–10 cm ranged from 0.19 g cm^{-3} for moor-silt to 0.28 g cm^{-3} for peat, lower than those reported for an alpine peatland on the Qinghai-Tibetan Plateau which had mean values from. 0.20 to 0.49 g cm^{-3} at core depths of 72 to 444 cm (Chen *et al*. 2014). Drollinger *et al.* (2020) obtained even lower BD values ranging from 0.045 g cm^{-3} in the top layers to 0.104 g cm^{-3} at a depth of 48 cm. In a study on the peat carbon stock of French peatlands, Pinault *et al*. (2023) generally observed lower BD values and, consequently, carbon stocks, in mountain compared to plain locations. Although alpine peatlands generally have lower BD values than their boreal counterparts, we highlight that peat soils can vary considerably in their physical properties depending on the decomposition degree, material source, bedding and vegetation cover (Osman 2018).

Regarding the BD values at different depths, some authors have noted that the BD of peat increases with depth (Howard *et al.* 1994, Milne & Brown 1997). However, according to more recent studies, this is not always the case, and BD shows either no change (Tomlinson & Davidson 2000, Lewis *et al.* 2011, Wellock *et al*. 2011) or a slight increase (Weiss *et al*. 2002) with depth. Therefore, the increase in BD with depth due to compression, which is often assumed in peat carbon stock modelling, may be inaccurate and may result in an overestimation of peat carbon stocks.

The C stocks in peatlands can be estimated using the peat volume, carbon density and time history approaches, all of which require information on the current peatland area (Yu 2012). In this study, we used the carbon density approach to determine the carbon stock of the alpine fen at Platzertal. This approach is one of the common approaches used for scaling up the carbon stocks for different biomes based on the average or representative carbon density value. In peatland soils, this approach is generally preferred as it accounts for the unique, often low-density structure of peat soils, allowing a more tailored and accurate carbon stock estimation (Yu 2012).

Over the years, various methods for classifying peat-forming systems and their soils have been developed, each with its own specific focus (Lindsay 2018). Conflicts in definitions often arise concerning the minimum depth of the organic layer at the soil surface and the minimum percentage of organic carbon (Tanneberger *et al*. 2017, Xu *et al*. 2018, IPS 2021). This inconsistency poses challenges as it affects estimates of peatland extent and calculations of the volume and carbon content (Joosten 2010, IPS 2021). Although peat is generally defined as a substrate containing at least 65 % organic matter (Salimin *et al.* 2010), the threshold proportions of organic carbon, organic matter and ash that soils must contain to be considered peat vary between countries and disciplines (IPS 2021). This has implications for national and continental peatland inventories and, consequently, estimations of global peatland extent and carbon stocks (Tanneberger *et al*. 2017, Xu *et al*. 2018). In this study, we characterised the soils in the field as peat, peat-moor or moor-silt using the finger test. Whilst this approach allows rapid estimation of soil texture in the field, the results can be affected by the soil moisture content and the presence of organic matter, and are subject to observer bias. Irrespective of the assigned soil type, all soils in our study area can be referred to as "peat-like soils" with similar properties. This is reflected in the similar SOC values, with 19.84 % for peat, 20.86 % for peat-moor and 20.29 % for moor-silt samples. However, contrary to our expectations, the BD value was lowest for the moor-silt soil, with an average of 0.21 g cm^{-3}, and highest for the peat soil, with a mean value of 0.34 g cm^{-3}. This phenomenon can be attributed to the inherent complexity of soil classification in alpine regions, where a distinct categorisation into discrete soil types is often impractical. A defining characteristic of alpine peatlands is their occurrence within transitional or mixed zones, leading to partial mixing of their interlayers with silt. In the study area, interstitial silt deposits have formed as a result of sedimentation from adjacent streams as well as colluvial deposits originating from surrounding slopes.

So far, there is a limited number of studies on the carbon stocks of alpine peatlands and their role in carbon sequestration. The low peat layer depth of the Platzertal fen area, which is largely covered by *Carex* communities, indicates a low carbon stock when compared to that of boreal peatlands, irrespective of the vegetation cover. Carbon stock estimates for wetlands or peatlands are often provided as part of global soil or ecosystem carbon stock estimates (Schlesinger 1977, Post *et al*. 1982, Adams & Faure 1998). We obtained a total carbon stock of 282 t (40 t ha^{-1}) for our study area, based on a peat volume of 6,223 m^3 and an average SOC level of 20.19 % of the dry soil weight. The stored CO_2 of the entire fen area (7.11 ha) therefore amounts to 1,035 t, with approximately 146 t ha^{-1}. In a study on the peatland carbon stores in the Snowy Mountains, Australia, Hope & Nanson (2014) observed an average carbon stock of *Sphagnum* bogs in sub-alpine and alpine areas of 200 t ha^{-1}, whereas in montane and sub-alpine *Carex* fens, the carbon stock amounted to 750 t ha^{-1}. For tropical peat swamp forests, an average carbon stock of 930 t ha^{-1} has been reported (Siregar & Narendra 2021), whereas values of up to 800 t ha^{-1} have been reported for low-mountain peatland forests (Krüger *et al.* 2015). The authors of a study on forest peatlands in Switzerland found mean soil carbon stocks of 495 t ha^{-1}, ranging from approximately 200 to 900 t ha^{-1} (Wüst-Galley *et al*. 2016). Much larger values have been reported for the northern boreal areas, with over 1,000 t ha^{-1} in deeper soils of peatland forests in Finland (Minkinnen *et al*. 1999). Although the carbon stock of alpine peatlands appears relatively low when compared to that of boreal regions, it is essential to evaluate these values within a global context that also includes non-peat soils. For instance, Perruchoud *et al*. (2010) reported a mean SOC stock of 98 t ha^{-1} for the entire mineral soil profile in forest soils of the Swiss Alps. Even lower SOC values have been documented for eucalypt plantations in Portugal, which exhibit an average of only 41.2 t ha^{-1} in the upper 30-cm layer (Quintela *et al*. 2024). These findings align with data from other studies that have reported average SOC stocks of 108 t ha^{-1} in mineral soils of European forests to a depth of 100 cm (De Vos *et al*. 2015) and SOC values ranging from 11.3 to 126.3 t ha^{-1} for the upper 20-cm soil layer (Baritz *et al*. 2010). In this context, the importance of alpine peatlands as carbon reservoirs takes on a new significance, highlighting the necessity of their inclusion in global carbon inventory assessments.

The carbon stock values obtained using the carbon density approach are generally lower (Schlesinger 1977, Post *et al.* 1982, Oechel 1989), which should be kept in mind when interpreting the values found in the current study involving a peatland area of only 7.11 ha. However, given the large differences between the carbon stock of the alpine mire investigated in the present study and the stocks of other (especially boreal) peatlands, the evaluation method chosen plays a minor role. Generally, carbon stock calculations are mainly affected by the values of carbon concentration, BD and peat layer thickness (Krüger *et al*. 2015, Wüst-Galley *et al.* 2016, Glina *et al.* 2019), which was also the case in the present study.

Although pristine peatlands are commonly considered to be carbon sinks, their CO_2 dynamics are characterised by high spatial and temporal variability and affected by factors such as temperature, vegetation, water table level and pH, which are often interrelated (Yu *et al.* 2001, Blodau & Moore 2003, Mäkiranta *et al*. 2010, Ireland *et al.* 2013, Mathijssen *et al.* 2016, Ratcliffe *et al*. 2020, Mozafari *et al*. 2023). Therefore, estimating potential CO_2 emissions from disturbed peatlands is complex. In the present study, the carbon fluxes were not accounted for, and our calculated CO_2 stock needs to be understood as an approximate value. It should be emphasised that alpine peatlands, like their boreal counterparts, can be either sinks or sources of carbon, depending on the environmental conditions and the season (Schneider 2010, Maanavilja *et al*. 2011). For example, an alpine peatland in northern Italy acted as a carbon source over the study period of three years, with CO_2 emissions considerably higher than those reported for other untouched peatland areas (Pullens *et al*. 2016). The authors partly explain this in terms of the short growing season and, consequently, the significantly shorter active carbon uptake period. Similar conditions occur at Platzertal, which, at an elevation of 2,300 m, would have an even shorter growing season, moving this area towards being a carbon source rather than a carbon sink. This assumption is further supported by the low abundance of *Sphagnum* and *Carex* species, which facilitate peat formation and accumulation. Nevertheless, with a changing climate, the snow cover period is expected to be shorter and the growing season longer, along with potential changes in vegetation cover and microbial activity, which might affectct the future role of Platzertal as carbon sink or source.

Although extensive research has been conducted on the carbon sequestration potential and stocks of peatlands, alpine peatlands have, so far, largely been overlooked. This oversight is concerning because, while they occupy significantly smaller areas than mineral soils, they store greater amounts of carbon per unit area. In Central Europe, approximately 90 % of all peatland areas have been destroyed, primarily due to peat extraction and draining. The remaining intact peatlands are predominantly located in high-elevation alpine areas. However, these alpine peatlands remain largely unrecorded and understudied, and this lack of information is a major shortcoming. Alpine peatlands, which rely on cool and moist conditions, are highly sensitive to climatic changes and human activities. Additionally, the sparse peat-forming vegetation, combined with the effects of livestock grazing that impede peat accumulation, often results in alpine peatlands being characterised by thin or even absent peat layers. The mosaic of swamps in Platzertal, investigated in this study as a representative alpine peatland area, exemplifies these characteristics. Whilst alpine peatlands hold considerable ecological importance and provide numerous ecosystem services, their role as soil carbon reservoirs is relatively minor when compared to the vast boreal peatlands of the Northern Hemisphere. However, in the context of a changing climate, the function of alpine peatlands as carbon reservoirs may be significantly altered.

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AUTHOR CONTRIBUTIONS

GE conceived and designed the study, undertook data collection and was involved in the writing of the manuscript; MP performed the literature research and wrote the manuscript; MK undertook data collection and analysis, prepared the Figures and provided a first draft of the manuscript; AS and MS were involved in the study design and the writing of the manuscript.

REFERENCES

Adams, J.M., Faure, H. (1998) A new estimate of changing carbon storage on land since the last glacial maximum, based on global land ecosystem reconstruction. *Global and Planetary Change*, 16–17, 3–24. https://doi.org/10.1016/S0921-8181(98)00003-4

Antala, M., Juszczak, R., van der Tol, C., Rastogi, A. (2022) Impact of climate change-induced alterations in peatland vegetation phenology and composition on carbon balance. *Science of the Total Environment*, 827, 154294. https://doi.org/10.1016/J.SCITOTENV.2022.154294

Assiri, M., Sartori, A., Vignoli, G., Massironi, M., Silvestri, S. (2022) Characterizing Alpine peatlands from drones: a case study. EGU22-1537, *Proceedings of the 24th EGU General Assembly*, Vienna. Online at: EGU22-1537-print.pdf, accessed 02 Sep 2025.

Balode, L., Bumbiere, K., Sosars, V., Valters, K., Blumberga, D. (2024) Pros and cons of strategies to reduce greenhouse gas emissions from peatlands: Review of possibilities. *Applied Sciences*, 14(6), 2260, 27 pp.

Baritz, R., Seufert, G., Montanarella, L., Van Ranst,

E. (2010) Carbon concentrations and stocks in forest soils of Europe. *Forest Ecology and Management*, 260, 262–277.

Blake, G.R., Hartge, K.H. (2018) Bulk density. In: Klute, A. (ed.) *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. Second edition, Agronomy Monograph 9, American Society of Agronomy - Soil Science Society of America, Madison, SSSA Book Series, 363–375. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Blodau, C., Moore, T.R. (2003) Micro-scale CO_2 and CH_4 dynamics in a peat soil during a water fluctuation and sulfate pulse. *Soil Biology and Biochemistry*, 35(4), 535–547. https://doi.org/10.1016/S0038-0717(03)00008-7

Bowman, W.D., Fisk, M.C. (2001) Primary production (Chapter 9). In: Bowman, W.D., Seastedt, T.R. (eds.) *Structure and Function of an Alpine Ecosystem: Niwot Ridge, Colorado*, Oxford University Press, NewYork, 177–197.

Brovkin, V., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., Andreev, A. (2002) Carbon cycle, vegetation, and climate dynamics in the Holocene: Experiments with the CLIMBER-2 model. *Global Biogeochemical Cycles*, 16(4), 1139, 20 pp. https://doi.org/10.1029/2001GB001662

Buytaert, W., Célleri, R., De Bièvre, B., Cisneros, F., Wyseure, G., Deckers, J., Hofstede, R. (2006) Human impact on the hydrology of the Andean páramos. *Earth-Science Reviews*, 79(1–2), 53–72. https://doi.org/10.1016/J.EARSCIREV.2006.06.002

Chen, H., Yang, G., Peng, C., Zhang, Y., Zhu, D., Zhu, Q., Hu, J., Wang, M., Zhan, W., Zhu, E., Bai, Z., Li, W., Wu, N., Wang, Y., Gao, Y., Tian, J., Kang, X., Zhao, X., Wu, J. (2014) The carbon stock of alpine peatlands on the Qinghai-Tibetan Plateau during the Holocene and their future fate. *Quaternary Science Reviews*, 95, 151–158. https://doi.org/10.1016/J.QUASCIREV.2014.05.003

Cooper, D.J., Chimner, R.A., Merritt, D.M. (2012) Western mountain wetlands. In: Batzer, D.P., Baldwin, A.H. (eds.) *Wetland Habitats of North America: Ecology and Conservation Concerns*, University of California Press, Oakland CA, 313–328).

Craft, C. (2016) Peatlands (Chapter 7). In: Craft, C. *Creating and Restoring Wetlands: From Theory to Practice*, Elsevier, 161–192.

Crnobrna, B., Llanqui, I.B., Cardenas, A.D., Panduro Pisco, G. (2022) Relationships between organic matter and bulk density in Amazonian peatland soils. *Sustainability*, 14(19), 12070, 14 pp. https://doi.org/10.3390/su141912070

Dettmann, U., Frank, S., Wittnebel, M., Piayda, A., Tiemeyer, B. (2022) How to take volume-based peat samples down to mineral soil? *Geoderma*, 427, 116132, 12 pp. https://doi.org/10.1016/j.geoderma.2022.116132

De Vos, B., Cools, N., Ilvesniemi, H., Vesterdal, L., Vanguelova, E., Carnicelli, S. (2015) Benchmark values for forest soil carbon stocks in Europe: Results from a large scale forest soil survey. *Geoderma*, 251–252, 33–46.

Diessel, C.F.K. (1992) The conditions of peat formation. In: Diessel, C.F.K. *Coal-Bearing Depositional Systems*, Springer-Verlag, Berlin Heidelberg, 5–39.

Dise, N.B. (2009) Peatland response to global change. *Science*, 326(5954), 810–811. https://doi.org/10.1126/science.1174268

Drollinger, S., Knorr, K.H., Knierzinger, W., Glatzel, S. (2020) Peat decomposition proxies of Alpine bogs along a degradation gradient. *Geoderma*, 369, 114331. https://doi.org/10.1016/J.GEODERMA.2020.114331

Egger, G., Kucher, T. (2023) *Ausbau Kraftwerk Kaunertal. Fachbeitrag Boden, Revision 3* (*Kaunertal Power Plant Expansion. Technical Report on Soil, Revision 3*). Report AK 960-0017b, Naturraumplanung Egger e.U./eb&p Umweltbüro gmbH, Klagenfurt, 145 pp. (in German).

Franchini, A.G., Henneberger, R., Aeppli, M., Zeyer, J. (2014) Methane dynamics in an alpine fen: a field-based study on methanogenic and methanotrophic microbial communities. *FEMS Microbiology Ecology*, 91(3), fiu032, 13 pp. https://doi.org/10.1093/femsec/fiu032

Glina, B., Gajewski, P., Mendyk, L., Zawieja, B., Kacumarek, Z. (2019) Recent changes in soil properties and carbon stocks in fen peatlands adjacent to open-pit lignite mines. *Land Degradation and Development*, 30(18), 2371–2380.

Gorham, E. (1991) Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, 1(2), 182–195.

Grab, S.W., Deschamps, C.L. (2004) Geomorphological and geoecological controls and processes following gully development in alpine mires, Lesotho. *Arctic, Antarctic, and Alpine Research*, 36(1), 49–58.

Hatala, J.A., Detto, M., Sonnentag, O., Deverel, S.J., Verfaillie, J., Baldocchi, D.D. (2012) Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-

San Joaquin Delta. *Agriculture, Ecosystems & Environment*, 150, 1–18. https://doi.org/10.1016/J.AGEE.2012.01.009

Hauer, F.R., Stanford, J.A., Lorang, M.S. (2007) Pattern and process in Northern Rocky Mountain headwaters: Ecological linkages in the headwaters of the Crown of the Continent. *Journal of the American Water Resources Association*, 43(1), 104–117.

Hope, G.S., Nanson, R.A. (2014) Peatland carbon stores and fluxes in the Snowy Mountains, New South Wales, Australia. *Mires and Peat*, 15, 11, 23 pp.

Howard, P., Loveland, P., Bradley, R., Dry, F., Howard, D. (1994) The carbon content of soil and its geographical distribution in Great Britain. *Soil Use and Management*, 11, 9–15.

Hribljan, J.A., Hough, M., Lilleskov, E.A., Suarez, E., Heckman, K., Planas-Clarke, A.M., Chimner, R.A. (2024) Elevation and temperature are strong predictors of long-term carbon accumulation across tropical Andean mountain peatlands. *Mitigation and Adaptation Strategies for Global Change*, 29, 1, 20 pp. https://doi.org/10.1007/s11027-023-10089-y

Huat, B.B.K., Kazemian, S., Prasad, A., Barghchi, M. (2011) State of an art review of peat: General perspective. *International Journal of the Physical Sciences,* 6(8), 1988–1996.

IPS (2021) What is peat? Web page, International Peatland Society (IPS), Jyväskylä. Online at: https://peatlands.org/peat/peat/, accessed 27 Mar 2025.

Ireland, A.W., Booth, R.K., Hotchkiss, S.C., Schmitz, J.E. (2013) A comparative study of within-basin and regional peatland development: implications for peatland carbon dynamics. *Quaternary Science Reviews*, 61, 85–95. https://doi.org/10.1016/J.QUASCIREV.2012.10.035

Ivanovs, J., Haberl, A., Melniks, R. (2024) Modeling geospatial distribution of peat layer thickness using machine learning and aerial laser scanning data. *Land*, 13(4), 466, 14 pp. https://doi.org/10.3390/land13040466

Joosten, H. (2010) *The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in all Countries of the World*. Wetlands International, Ede, the Netherlands, 33 pp.

Joosten, H., Clarke, D. (2002) *Wise Use of Mires and Peatlands: Background and Principles Including a Framework for Decision-Making*. International Peat Society, Jyväskylä, 304 pp.

Kleinen, T., Brovkin, V., von Bloh, W., Archer, D., Munhoven, G. (2010) Holocene carbon cycle dynamics. *Geophysical Research Letters*, 37(2), L02705, 5 pp. https://doi.org/0.1029/2009GL041391

Kløve, B., Sveistrup, T.E., Hauge, A. (2010) Leaching of nutrients and emission of greenhouse gases from peatland cultivation at Bodin, Northern Norway. *Geoderma*, 154(3–4), 219–232. https://doi.org/10.1016/J.GEODERMA.2009.08.022

Koch, O. (2007) *Carbon and Nitrogen Transformations in Alpine Ecosystems of the Eastern Alps, Austria*. Doctoral thesis, Universität Hohenheim, 86 pp.

Kõlli, R., Asi, E., Tõnutare, T., Astover, A., Szajdak, L., Tamm, I. (2016) Fabric and properties of mineral soils underlying a shallow peat mantle in Estonia. *Quaternary International*, 418, 84–93. https://doi.org/10.1016/J.QUAINT.2015.08.045

Körner, C. (1999) Uptake and loss of carbon. In: Körner, C. *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*, Springer-Verlag, Berlin Heidelberg, 171–200.

Krisai, R. (1998) Moore im Ostalpenraum: Entstehung und Vegetation (Mires in the Eastern Alps: Distribution, development and present day vegetation). *TELMA*, 28, 11–24 (in German with English summary).

Krüger, J.P., Leifeld, J., Glatzel, S., Szidat, S., Alewell, C. (2015) Biogeochemical indicators of peatland degradation - a case study of a temperate bog in northern Germany. *Biogeosciences*, 12(10), 2861–2871.

Laine, A. M., Mehtätalo, L., Tolvanen, A., Frolking, S., Tuittila, E.S. (2019) Impacts of drainage, restoration and warming on boreal wetland greenhouse gas fluxes. *Science of The Total Environment*, 647, 169–181. https://doi.org/10.1016/J.SCITOTENV.2018.07.390

Leng, L.Y., Ahmed, O.H., Jalloh, M.B. (2019) Brief review on climate change and tropical peatlands. *Geoscience Frontiers*, 10(2), 373–380. https://doi.org/10.1016/J.GSF.2017.12.018

Lewis, C., Albertson, J., Xu, X., Kiely, G. (2011) Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Ecohydrology*, 26(10), 1527–1537.

Liebner, S., Schwarzenbach, S.P., Zeyer, J. (2011) Methane emissions from an alpine fen in central Switzerland. *Biogeochemistry*, 109, 287–299.

Lindsay, R. (2018) Peatland classification. In: Finlayson, C.M., Everard, M., Irvine, K., McInnes, R.J., Middleton, B.A., van Dam, A.A., Davidson, N.C. (eds.) *The Wetland Book: I:*

Structure and Function, Management, and Methods, Springer, Netherlands, 1515–1528.

Maanavilja, L., Riutta, T., Aurela, M., Pulkkinen, M., Laurila, T., Tuittila, E.-S. (2011) Spatial variation in CO_2 exchange at a northern aapa mire. *Biogechemistry*, 104, 325–345.

Mäkiranta, P., Riutta, T., Penttilä, T., Minkkinen, K. (2010) Dynamics of net ecosystem CO_2 exchange and heterotrophic soil respiration following clearfelling in a drained peatland forest. *Agricultural and Forest Meteorology*, 150(12), 1585–1596. https://doi.org/10.1016/J.AGRFORMET.2010.08.010

Mathijssen, P.J.H., Väliranta, M., Korrensalo, A., Alekseychik, P., Vesala, T., Rinne, J., Tuittila, E.S. (2016) Reconstruction of Holocene carbon dynamics in a large boreal peatland complex, southern Finland. *Quaternary Science Reviews*, 142, 1–15. https://doi.org/10.1016/J.QUASCIREV.2016.04.013

Menviel, N., Joos, F. (2012) Toward explaining the Holocene carbon dioxide and carbon isotope records: Results from transient ocean carbon cycle-climate simulations. *Paleoceanography and Paleoclimatology*, 27(1), PA1207, 17 pp. https://doi.org/10.1029/2011PA002224

Mestdagh, I., Lootens, P., Van Cleemput, O., Carlier, L. (2006) Variation in organic-carbon concentration and bulk density in Flemish grassland soils. *Journal of Plant Nutrition and Soil Science,* 169(5), 616–622.

Millar, D.J., Cooper, D J., Dwire, K.A., Hubbard, R.M., Ronayne, M.J., von Fischer, J. (2023) Hydrological dynamics and associated greenhouse gas fluxes in a mountain peatland under different climate scenarios. *Ecohydrology*, 16(5), e2536, 12 pp.

Milne, R., Brown, T.A. (1997) Carbon in the vegetation and soils of Great Britain. *Journal of Environmental Management*, 49(4), 413–433. https://doi.org/10.1006/JEMA.1995.0118

Minayeva, T.Yu., Sirin, A.A. (2012) Peatland biodiversity and climate change. *Biology Bulletin Reviews*, 2, 164–175.

Minkinnen, K., Vasander, H., Jauhiainen, S., Karsisto, M., Laine, J. (1999) Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. *Plant and Soil*, 207, 107–120.

Mitsch, W.J., Gosselink, J.G. (2000) The value of wetlands: importance of scale and landscape setting. *Ecological Economics*, 35(1), 25–33. https://doi.org/10.1016/S0921-8009(00)00165-8

Monge-Salazar, M.J., Tovar, C., Cuadros-Adriazola, J., Baiker, J.R., Montesinos-Tubée, D.B., Bonnesoeur, V., Antiporta, J., Román-Dañobeytia, F., Fuentealba, B., Ochoa-Tocachi, B.F., Buytaert, W. (2022) Ecohydrology and ecosystem services of a natural and an artificial bofedal wetland in the central Andes. *Science of the Total Environment*, 838, 155968, 14 pp. https://doi.org/10.1016/J.SCITOTENV.2022.155968

Moore, T.R., Knowles, R. (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science*, 69(1), 33–38.

Mozafari, B., Bruen, M., Donohue, S., Renou-Wilson, F., O'Loughlin, F. (2023) Peatland dynamics: A review of process-based models and approaches. *Science of the Total Environment*, 877, 162890, 17 pp. https://doi.org/10.1016/J.SCITOTENV.2023.162890

Mucina, L., Ellmauer, Th., Wallhöfer, S. (1993) *Die Pflanzengesellschaften Österreichs* (*The Plant Communities of Austria*). Gustav Fischer, Jena, 1454 pp. (in German).

Oechel, W.C. (1989) Nutrient and water flux in a small arctic watershed: an overview. *Ecography*, 21(3), 229–237.

Ojanen, P., Minkkinen, K., Penttilä, T. (2013) The current greenhouse gas impact of forestry-drained boreal peatlands. *Forest Ecology and Management*, 289, 201–208. https://doi.org/10.1016/J.FORECO.2012.10.008

O´Reilley, B.C. (2011) *Paleoecological and Carbon Accumulation Dynamics of a Fen Peatland in the Hudson Bay Lowlands, Northern Ontario, from the Mid-Holocene to Present*. Doctoral thesis, University of Toronto, 120 pp.

Osman, K.T. (2018) Peat soils. In: Osman, K.T. *Management of Soil Problems*, Springer International Publishing AG, Cham, 145–183.

Paniagua, P., Long, M., l'Heureux, J.S. (2021) Geotechnical characterization of Norwegian peat: database. *IOP Conference Series: Earth and Environmental Science*, 710(1), 012016, 8 pp. https://doi.org/10.1088/1755-1315/710/1/012016

Parish, F., Sirin, A.A., Charman, D., Joosten, H., Minaeva, T.Yu., Silvius, M., Stringer, L. (eds.) (2008) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen, 179 pp.

Paternoster, D., Danzinger, F., Koukal, T., Kudrnovsky, H., Lackner, S., Berger, A., Schadauer, K., Wrbka, T., Stejskal-Tiefenbach, M., Ellmauer, T. (2021) *Strategischer Rahmen für eine Priorisierung zur Wiederherstellung von Ökosystemen auf nationalem und subnationalem Niveau. Endbericht*. (*Strategic Framework for Prioritising Ecosystem Restoration at the National and Subnational Levels. Final Report*). Umweltbundesamt, Vienna, 147 pp. (in German).

Perruchoud, D., Walthert, L., Zimmermann, S., Luscher, P. (2010) Contemporary carbon stocks of mineral forest soils in the Swiss Alps. *Biogeochemistry*, 50, 111–136.

Pinault, N., Pilloix, M., Bernard, G., Joly, D., Gogo, S., Martin, E., Gilbert, D. (2023) The 1949 Atlas of French peat deposits, a starting point for a National Inventory of peatlands. *Soil Use and Management*, 39(3), 1040–1056.

Post, W.M., Emanuel, W.R., Zinke, P.J., Stangenberger, A.C. (1982) Soil carbon pools and world life zones. *Nature*, 298(5870), 156–159.

Pullens, J.W.M., Sottocornola, M., Kiely, G., Toscano, P., Gianelle, D. (2016) Carbon fluxes of an alpine peatland in Northern Italy. *Agricultural and Forest Meteorology*, 220, 69–82. https://doi.org/10.1016/J.AGRFORMET.2016.01.012

Quintela, A., Ferreira, D., Fabres, S., Coutinho, J. (2024) A survey of organic carbon stocks in mineral soils of *Eucalyptus globulus* Labill. plantations under Mediterranean climate conditions. *Forests*, 15(8), 1335, 14 pp. https://doi.org/10.3390/f15081335

Ratcliffe, J.L., Campbell, D. I., Schipper, L.A., Wall, A.M., Clarkson, B.R. (2020) Recovery of the CO_2 sink in a remnant peatland following water table lowering. *Science of the Total Environment*, 718, 134613, 12 pp. https://doi.org/10.1016/J.SCITOTENV.2019.134613

Reeburgh, W.S., King, J.Y., Regli, S.K., Kling, G.W., Auerbach, N.A., Walker, D.A. (1998) A CH_4 emission estimate for the Kuparuk River basin, Alaska. *Atmospheres*, 103(D22), 29005–29013. https://doi.org/10.1029/98JD00993

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R., Bubier, J. (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13(2), 397–411.

Sakin, E. (2012) Organic carbon, organic matter and bulk density relationships in arid - semi arid soils in Southeast Anatolia region. *African Journal of Biotechnology*, 11(6), 1373–1377.

Salimin, M.I., Gandaseca, S., Ahmed, O.H., Majid, N.M.A. (2010) Comparison of selected chemical properties of peat swamp soil before and after timber harvesting. *American Journal of Environmental Science*, 6(2), 164–167.

Sass, O., Wetzel, K.F., Friedmann, A. (2006) Landscape dynamics of sub-alpine forest fire slopes in the Northern Alps - Preliminary results. *Zeitschrift für Geomorphologie Supplement*, 142, 207–227.

Schlesinger, W.H. (1977) Carbon balance in terrestrial detritus. *Annual Review of Ecology and Systematics*, 8, 51–81.

Schlesinger, W.H., Andrews, J.A. (2000) Soil respiration and the global carbon cycle. *Biogeochemistry*, 48, 7–20.

Schneider, J. (2010) *Dynamics of CO_2 Fluxes from Boreal Peatlands*. PhD thesis, Ernst-Moritz-Arnd-Universität, Greifswald, 172 pp.

Sheng, Y., Smith, L.C., MacDonald, G.M., Kremenetski, K.V., Frey, K.E., Velichko, A.A., Lee, M., Beilmann, D.W., Dubinin, P. (2004) A high-resolution GIS-based inventory of the west Siberian peat carbon pool. *Global Biogeochemical Cycles*, 18(3), GB3004, 14 pp. https://doi.org/10.1029/2003GB002190

Siregar, C.A., Narendra, B.H. (2021) Assessment of soil carbon stocks in several peatland covers in Central Kalimantan, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 914, 012045, 8 pp. https://doi.org/10.1088/1755-1315/914/1/012045

Spieles, D.J. (2022) Wetland construction, restoration, and integration: A comparative review. *Land*, 11(4), 554, 21 pp. https://doi.org/10.3390/land11040554

Tanneberger, F., Tegetmeyer, C., Busse, S., Barthelmes, A. (2017) The peatland map of Europe. *Mires and Peat*, 19, 22, 17 pp. https://doi.org/10.19189/MaP.2016.OMB.264

Tarnocai, C., Stolbovoy, V. (2006) Chapter 2 Northern Peatlands: their characteristics, development and sensitivity to climate change. *Developments in Earth Surface Processes*, 9(C), 17–51. https://doi.org/10.1016/S0928-2025(06)09002-X

Thien, S.J. (1979) A flow diagram for teaching texture by feel analysis. *Journal of Agronomic Education*, 8, 54–55.

Tomlinson, R.W., Davidson, L. (2000) Estimates of carbon stores in four Northern Irish lowland raised bogs. *Suoseura*, 51(3), 169–167.

Tuittila, E.S., Juutinen, S., Frolking, S., Väliranta, M., Laine, A.M., Miettinen, A., Seväkivi, M.-J., Quillet, A., Merilä, P. (2012) Wetland chronosequence as a model of peatland development: Vegetation succession, peat and carbon. *The Holocene*, 23(1), 25–35. https://doi.org/10.1177/0959683612450197 van Asselen, S., Erkens, G., Stouthamer, E., Woolderink, H.A.G., Geeraert, R.E.E., Hefting, M.M. (2018) The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, The Netherlands. *Science of the Total Environment*, 636, 177–191. https://doi.org/10.1016/J.SCITOTENV.2018.04.141

Vitt, D.H., Halsey, L.A., Nicholson, B.J. (2005) The Meckenzie River basin. In: Fraser, L.H., Keddy, P.A. (eds.) *The World´s Largest Wetlands: Ecology and Conservation*, Cambridge University Press, 166–202.

Vroom, R.J.E., van den Berg, M., Pangala, S.R., van der Scheer, O.E., Sorrell, B.K. (2022) Physiological processes affecting methane transport by wetland vegetation - A review. *Aquatic Botany*, 182, 103547, 13 pp. https://doi.org/10.1016/J.AQUABOT.2022.103547

Weil, R.R., Magdoff, F. (2004) Significance of soil organic matter to soil quality and health. In: Weil R.R., Magdoff, F. (eds.) *Soil Organic Matter in Sustainable Agriculture*, CRC Press, Boca Raton, 1–43.

Weiss, D., Shotyk, W., Rieley, J., Page, S., Gloor, M., Reese, S., Martinez-Cortizas, A. (2002) The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition. *Geochimica et Cosmochimica Acta*, 66(13), 2307–2323. https://doi.org/10.1016/S0016-7037(02)00834-7

Wellock, M.L., Reidy, B., Laperle, C.M., Bolger, T., Kiely, G. (2011) Soil organic carbon stocks of afforested peatlands in Ireland. *Forestry*, 84(4), 441–451. https://doi.org/10.1093/forestry/cpr046

Whiting, G.J., Chanton, J.P. (1992) Plant-dependent CH_4 emission in a subarctic Canadian fen. *Global Biogeochemical Cycles*, 6(3), 225–231.

Wittmann, H., Stöhr, O., Krisai, R., Gewolf, S., Frühwirth, S., Rücker, T., Dämon, W. (2007) *Erfassung der Moore im Nationalpark Hohe Tauern in den Bundesländern Kärnten, Salzburg und Tirol* (*Survey of the Mires in the Hohe Tauern National Park in the Federal States of Carinthia, Salzburg and Tyrol*). Final report, „Pflanzen-soziologische und standortökologische Untersuchung der Moore des NPHT“ (“Plant Sociological and Site-Ecological Investigation of the NPHT Bogs”), Institut für Ökologie (IfÖ) Haus der Natur, Elsbethen, 389 pp. (in German).

Woodhurst, G.D., de Scally, F.A. (2017) Sediment loading of alpine debris-flow channels by snow avalanches, Canadian Rocky Mountains. *Geografiska Annaler: Series A, Physical Geography*, 100(1), 4–26.

Wunderlich, W., Lang, M., Keating, K., Perez, W.B., Oshun, J. (2023) The role of peat-forming bofedales in sustaining baseflow in the humid puna. *Journal of Hydrology: Regional Studies*, 47, 101394. https://doi.org/10.1016/J.EJRH.2023.101394

Wüst-Galley, C., Mössinger, E., Leifeld, J. (2016) Loss of the soil carbon storage function of drained forest peatlands. *Mires and Peat*, 18, 07, 22 pp.

Xu, J., Morris, P.J., Liu, J., Holden, J. (2018) PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*, 160, 134–140.

Yu, Z.C. (2012) Northern peatland carbon stocks and dynamics: a review. *Biogeosciences*, 9(10), 4071–4085. https://doi.org/10.5194/bg-9-4071-2012

Yu, Z., Campbell, I.D., Vitt, D.H., Apps, M.J. (2001) Modelling long-term peatland dynamics. I. Concepts, review, and proposed design. *Ecological Modelling*, 145(2–3), 197–210. https://doi.org/10.1016/S0304-3800(01)00391-X

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