Geoderma 427 (2022) 116132

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

How to take volume-based peat samples down to mineral soil?

Ullrich Dettmann [a,b,1,*], Stefan Frank [a,1], Mareille Wittnebel [a], Arndt Piayda [a], Bärbel Tiemeyer [a]

[a] Thünen Institute of Climate-Smart Agriculture, Bundesallee 65a, 38116 Braunschweig, Germany
[b] Institute of Soil Science, Leibniz University Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany

ARTICLE INFO

Handling Editor: Haly Neely

Keywords:
Bulk density
Soil mass
Soil organic carbon stock
Intact soil samples
Undisturbed soil samples

ABSTRACT

Determination of soil organic carbon stocks in peat soils is of major importance for prioritization and evaluation of mitigation measures. This requires the accurate assessment of bulk density, which is commonly undertaken by measuring the oven-dry weight of a volume-based sample. Sample rings (steel cylinders) are widely used and have become the method of choice. If sample rings cannot be taken (e.g. in deep peat layer), sampling needs to be performed with other sampling devices. The aim of this study is to evaluate the accuracy and precision of different sampling devices in determining bulk density and total peat masses of the entire peat profiles down to mineral soil. Four sampling devices (driving hammer device with a sheath probe, gouge auger, Russian corer and Wardenaar corer) were compared with sample rings at one bog peat site and one fen peat site. The gouge auger and Russian corer – the only sampling devices in this study applicable for depths below approximately −1 m – were also compared with one another.

The results varied depending on peat type and horizon characteristics. Sample rings and the driving hammer were the only sampling devices that could be used to sample the amorphous or aggregated peat of the upper, unsaturated part of the profiles. However, samples taken with the driving hammer significantly underestimated bulk densities and thus caused a high systematic error of −0.068 g cm^{-3}. In the sampling depths with slightly to moderately decomposed peat, bulk density values determined with the driving hammer, gouge auger and Wardenaar corer were not significantly different from the data acquired using sample rings. At these depths, all the sampling devices had low systematic errors, with −0.002 g cm^{-3} for the gouge auger, 0.005 g cm^{-3} for the driving hammer, −0.006 g cm^{-3} for the Wardenaar corer and 0.012 g cm^{-3} for the Russian corer. The Russian corer caused an overestimation of bulk density in the unsaturated sampling depths, whereas in the saturated sampling depths, the values were similar to those determined with the gouge auger. Total peat masses determined using the tested sampling devices differed only slightly. As those devices which can acquire samples from the amorphous or aggregated horizons are not suited for deep peat profiles, a combination of different devices will be necessary for determining bulk density and thus soil organic carbon stocks at many peatland sites. We could show that this is a reliable approach when considering site-specific conditions.

1. Introduction

Peat soils are characterised by large amounts of soil organic carbon (SOC). Although peatlands cover only approximately 3 % of the global land surface (Tubiello et al., 2016; Leifeld and Menichetti, 2018), they are the ecosystems with the world's largest SOC stocks and thus have a major impact on the global C cycle (Yu et al., 2010). Peatlands are commonly defined on a hydrological basis. Bogs are ombrotrophic (rainfed) and fens are minerotrophic (groundwater-fed) (du Rietz, 1954). Peat mosses of the genus *Sphagnum* are the major peat forming species in bogs, while the vegetation of fens is more diverse comprising, among others peat and brown mosses, sedges and reed (Gorham, 1957). Due to drainage for agriculture and forestry, peatlands have become globally relevant sources of greenhouse gases (GHG) (Tubiello et al., 2016; Leifeld et al., 2019), mainly carbon dioxide (CO_2) (Frolking et al., 2011). In the light of accelerating climate change, rewetting measures to mitigate these emissions are urgently required (Günther et al., 2020). Repeated measurements of SOC stocks are one of the established methods to determine SOC losses (Simola et al., 2012). Further, for prioritizing and evaluation of mitigation measures the determination of

* Corresponding author at: Thünen Institute of Climate-Smart Agriculture, Bundesallee 65a, 38116 Braunschweig, Germany.
E-mail address: ullrich.dettmann@thuenen.de (U. Dettmann).
[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.geoderma.2022.116132
Received 22 July 2021; Received in revised form 9 August 2022; Accepted 23 August 2022
Available online 30 August 2022

SOC stocks and/or SOC stock changes is necessary (Agus et al., 2011). However, this requires accurate measurements of bulk densities (BD) down to mineral soil in order to calculate SOC stocks by multiplying SOC contents by the thickness of the respective soil layer and BD (Batjes, 1996).

Bulk density is commonly determined by measuring the oven-dry weight of a volume-based sample. Sample rings (steel cylinders) are widely used and have become the method of choice, following the international standard DIN EN ISO (2001). Besides sample rings, several core samplers are available that are either driven into the soil by a driving hammer or by hand. All devices aim to take a defined volume of an intact soil core. In mineral soil research, driving hammer devices, e.g. a sheath probe (Nordmeyer Geotool GmbH, Germany), window probe (Eijkelkamp, Netherlands) or liner probe (Carl Hamm GmbH, Germany), are popular (Don et al., 2007, Schrumpf et al., 2011, Walter et al., 2016). For peat soils, hand-driven devices such as the gouge auger (Eijkelkamp, Netherlands), Russian corer (Belarussian corer) (Belokopytov and Beresnevich, 1955; Jowsey, 1966, Agus et al., 2011) and Wardenaar corer (Wardenaar, 1987) are more popular. Shotyk and Noernberg (2020) provide an excellent overview of the different peat corers and their historical development.

Although these different sampling devices exist, volume-based sampling is difficult and additional challenges are posed by the specific properties of peat soils. First, depending on the original plant composition, the degree of decomposition and the degree of secondary pedogenetic transformation, the properties of peat soils are highly variable. For example, Zaccone et al. (2018) found BD down to 0.024 g cm^{-3} in a living sphagnum layer, while Wittnebel et al. (2021) found BD values of between 0.06 g cm^{-3} and 0.75 g cm^{-3} for bog and fen peat soils under agricultural use in Germany. Second, the consistency of the material can be very diverse depending on decomposition and the moisture status. Peat has a non-rigid matrix, and slightly decomposed peat in particular is very soft and easily compressible (O'Kelly and Pichan, 2013). In contrast, horizons in drained peatlands with a low water content may show strong aggregation or become single-grained in structure (Okruszko and Ilnicki, 2002). Third, if repeated measurements of SOC stocks are planned, sampling of the whole peat profile will be necessary (Wittnebel et al., 2021). Due to mineralisation and shrinkage, the peat volume does not remain constant over time, and thus a correction of SOC stocks to "constant mass", as frequently applied for mineral soils (Ellert and Bettany, 1995), is not possible.

The high variability of peat soils and peatlands requires the selection of a coring device that is appropriate for the respective peat soil properties and thickness of the peat profile. Sample rings have the advantages that the sampling protocol follows an international standard (DIN EN ISO, 2001) and that the height of the sample ring does not exceed the diameter, which is desirable to minimise the effect of disturbed soil interfacing the cylinder wall (Blake and Hartge, 1986). However, sampling requires a soil pit to be dug, which is time consuming and in greater depths challenging or even impossible. Further, in natural or near-natural peatlands, where the topsoil is dominated by a transition from living plants to very slightly decomposed fibrous peat, sampling with sample rings may present a challenge or may not even be possible. The Wardenaar corer (Wardenaar, 1987) has been specifically designed for such conditions (De Vleeschouwer et al., 2010). However, it might fail to sample unsaturated highly decomposed amorphous and aggregated peat at drained sites. It is also limited to a sampling depth of one metre. As in case of sample rings, this hampers sampling in greater depths, which is possible with a gouge auger or Russian corer. Still, these devices might not be able to sample slightly decomposed fibrous or highly decomposed amorphous and aggregated peat soil. Hence, a combination of different sampling devices might be a good option for covering different conditions of peat horizons from the surface down to the mineral soil. For example, Shotyk and Noernberg (2020) recommend the combination of the Wardenaar and Russian peat corers for trace element research. However, combining sampling devices requires that the BD values of samples obtained by these devices are not significantly different. In single-site studies, biases caused by a certain device might not be that problematic, but when attempting to determine the SOC stocks of a wide range of peatland types, for example in monitoring programmes, comparability is essential. To date, the accuracy in determining BD with a driving hammer device, gouge auger, Russian corer or Wardenaar corer has not been systematically evaluated and compared with sample rings, although the Russian corer in particular is widely used and recommended for taking volume-based samples (De Vleeschouwer et al., 2010; Agus et al., 2011; Wellock et al., 2011; Chimner et al., 2014).

Here, we present the first systematic comparison of different sampling devices based on extensive sampling campaigns at one bog peat site and one fen peat site. The aims were to: (1) investigate the applicability of different sampling devices for the acquisition of volume-based samples from peat soils with different degrees of decomposition, secondary pedogenetic transformation and moisture statuses, (2) determine eventual differences in the estimation of total peat masses over the whole profile down to the mineral soil caused by the different sampling devices and (3) identify the accuracy and precision of BD determined from samples taken with the different devices to derive recommendations for the choice of sampling devices. A driving hammer with a sheath probe, a gouge auger, a Russian corer and a Wardenaar corer were compared with sample rings as reference method. Additionally, the gouge auger and Russian corer were compared for greater depths from which no sample rings could be taken.

2. Materials and methods

2.1. Site description

The different sampling devices were compared at a fen peat site (53°20′56.0″ N, 8°58′39.0″ E) and a bog peat site (53°23′31.7″ N, 9°03′00.6″ E) under grassland use in Lower Saxony, Germany. Following the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) the fen peat site was classified as "Rheic Drainic Hemic Histosol" and the bog peat site as "Ombric Drainic Fibric Histosol". At each site a −1.0 m (fen peat site) and −1.2 m (bog peat site) deep and 19.2 m long soil pit was dug and separated into 12 segments each 1.6 m long. The soil horizons of the profiles were mapped in accordance with the German soil classification system (Ad-hoc-AG Boden, 2005) in every segment. The degree of decomposition was determined according to the von Post scale, which is based on the consistency of plant remains and soil water colour (von Post, 1922).

The upper horizons at both sites were characterized by amorphous peat. Below, the bog peat site was dominated by *Sphagnum* peat and the fen peat site by peat mainly composed of brown mosses and sedges. The basic descriptions of the soil profiles are given in Table 1 for the fen peat site and in Table 2 for the bog peat site. Soil organic carbon concentrations were determined by dry combustion (RC 612/TRUMEC, LECO Corporation, St. Joseph, USA) from separate samples taken from the profile wall in segment 1. The depths of the horizons were mean values and standard deviations determined for the 12 segments of the soil profile.

2.2. Sampling devices

The study was conducted with five different sampling devices: sample rings, a driving hammer (sheath probe, Eijkelkamp, Netherlands), a gouge auger (Eijkelkamp, Netherlands), a Russian corer (Belokopytov and Beresnevich, 1955; Jowsey, 1966) and a Wardenaar corer (Wardenaar, 1987). Photographs of these devices can be found in the Appendix.

All sampling devices have different sample volumes and geometries. The sample rings are designed with a sharpened lower edge and have the smallest volume with 244.29 cm^3 (height: 6 cm, diameter: 7.2 cm),

Table 1
Soil profile descriptions at the fen peat site. Lower depth of the mapped horizons (mean value and standard deviation of the 12 segments), peat type (botanical origin), degree of decomposition after von Post, soil organic carbon (SOC) content, horizon characteristics, name of sampling depth (D), lower depth of sampling depth (mean value and standard deviation), sampling devices used per sampling depth and statistical model (see Section 2.4.2).

Lower depth of the horizon [m]	Peat type [–]	Von Post [–]	SOC [%]	Horizon characteristics [–]	D [–]	Lower depth of D [m]	Sampling devices [–]	Model [–]
−0.20 ± 0.03	Amorphous	10	47.2	Transition from earthified, crumbly to “moorshy”, dusty and small-grained structure	F-D1*	−0.20 ± 0.03	Sample rings, driving hammer	M1
−0.32 ± 0.05	Amorphous with pockets of brown moss	9	55.6	Aggregated sub-polyhedral structure	F-D2*	−0.32 ± 0.05	Sample rings, driving hammer	M1
−0.75 ± 0.02	Brown moss with some sedges, reed and alder remains	4	58.3	Alternating saturated–unsaturated conditions	F-D3*	−0.75 ± 0.02	Sample rings, driving hammer, gouge auger, Russian corer	M2, M3
−1.05 ± 0.03	Brown moss with sedges	5	53.2	Permanently saturated conditions	F-D4*	−1.05 ± 0.03	Sample rings, driving hammer, gouge auger, Russian corer	M2, M3
−1.20 ± 0.00	Brown moss with sedges	6	–	Permanently saturated conditions			–	–

* sampling depths according to horizon boundaries.

followed by the Russian corer with a volume of 340 cm^3 (core length of 50 cm). The Russian corer is self-built and consists of a halved steel cylinder with a rotating steel blade and a sharpened end. Details can be found in Belokopytov and Beresnevich (1955) and Jowsey (1966). The gouge auger has the shape of a halved dodecagon and a volume of 1760 cm^3 (core length 100 cm; diameter 5.7 cm) and the driving hammer has a cylindric shape with a volume of 2827 cm^3 (core length 100 cm, inner diameter 6 cm). The Wardenaar corer takes cuboid samples (100 cm · 10 cm · 12 cm) and is the sampling device with the larges sample volumes (12000 cm^3). It consists of two opposite half-casings with curved cutting edges at the base held together by hinges. The hinges can either lock both half casings together or be loosened in order to alternately control each half. A detailed description can be found in Wardenaar (1987).

The maximum sampling depths varies for the different sampling devices. For the sample rings it is limited to the depth of the soil pit and for the driving hammer and Wardenaar corer to their respective core length of 1 m. The gouge auger and the Russian corer are the only sampling devices in this study allowing sampling in greater depths, as they can be extended with additional rods.

2.3. Soil sampling

Sampling was conducted at the driest time of the year (September), and groundwater levels were therefore around −1.05 m and −0.75 m at the bog and fen peat site, respectively. At the fen peat site, sampling was performed horizon-wise over the complete profile depth from −0.03 to −1.05 ± 0.03 m. It should be noted that no sampling was performed from 0.00 to −0.03 m due to an extremely densely rooted layer that was removed before sampling. At the bog peat site, sampling was performed horizon-wise from 0.00 to −1.00 m. For greater depths, samples were taken at depth increments, e.g. from −1.00 to −1.25 m, −1.25 to −1.50 m, and −1.50 to −2.00 m, continuing with 0.50 m steps down to the mineral soil. As horizon-wise and depth increment-wise sampling was combined within one soil profile, further reference is made to “sampling depth” with an increasing number, e.g. F-D1, F-D2, F-D3 and F-D4 for the fen peat site and B-D1, B-D2, B-D3, etc. for the bog peat site.

Table 1 (fen peat site) and Table 2 (bog peat site) show the sampling depths that are assigned to a horizon or depth increment. At the fen peat site, the horizon between −1.05 m and −1.20 m was only found in one segment and merged into sampling depth F-D4. At the bog peat site, horizons 1 and 2 were merged into one sampling depth (B-D1) because horizon 2 did not fulfil the minimum thickness criterion (~7 cm) throughout the entire 19.2 m-long soil profile. Furthermore, horizon 2 could not be found in all segments. Horizon 3 had varying von Post values from 2 to 4.

The sample rings were taken at both sites from the profile wall down to a depth of approximately −1 m (fen peat site) and −1.25 m (bog peat site). At every sampling depth, six sample rings were carefully inserted vertically into the soil. The whole sample was then excavated. After collection and careful cutting of protruding material using scissors and serrated knives, the peat was removed from the sample rings into separate plastic bags and stored at 6 °C. Depending on the thickness of the sampling depth, sample rings were taken from one, two or three depths within one sampling depth (Fig. 1).

Sampling with a driving hammer, gouge auger, Russian corer and Wardenaar corer was performed approximately 0.50 m behind the profile walls with the different sampling devices in randomised positions (Fig. 2). In every segment, the sampling positions were at a distance of 0.2, 0.6, 1.0 and 1.4 m along the profile wall. In the case of the gouge auger and Russian corer, samples were taken stepwise, alternating between two parallel holes with a distance of ±0.1 m from the original sampling position (e.g. for the sampling position at 0.2 m, the two parallel holes were at 0.1 and 0.3 m etc.). Each soil core was cut according to the sampling depth (determined either by horizon or depth increment) and the material stored in plastic bags.

Table 2
Soil profile descriptions of the bog peat site. Lower depth of the mapped horizons (mean value and standard deviation of the 12 segments), peat type (botanical origin), degree of decomposition after von Post, soil organic carbon (SOC) content, horizon characteristics, name of sampling depth (D), lower depth of sampling depth (mean value and standard deviation), sampling devices used per sampling depth and statistical model (see Section 2.4.2).

Lower depth of the horizon [m]	Peat type [–]	Von Post [–]	SOC [%]	Horizon characteristics [–]	D [–]	Lower depth of D [m]	Sampling devices [–]	Model [–]
−0.08 ± 0.02	Amorphous	10	46.3	Earthified crumbly structure, ploughed	B-D1*	−0.15 ± 0.03	Sample rings, driving hammer	M1
−0.15 ± 0.03	Amorphous peat mixed with *Sphagnum*, some dwarf shrub and cotton grass remains	10 partially mixed with 2–4	–	Alternating saturated–unsaturated conditions, partially ploughed and a mix of the upper and lower horizons				
−0.79 ± 0.06	*Sphagnum*, some dwarf shrub remains	2 – 4	52.4	Alternating saturated–unsaturated conditions	B-D2*	−0.79 ± 0.06	Sample rings, driving hammer, gouge auger, Russian corer, Wardenaar corer	M2, M3
−1.17 ± 0.16	*Sphagnum*, some dwarf shrub remains	2	55.0	Permanently saturated conditions	B-D3*	−1.00 ± 0.00	Sample rings, driving hammer, gouge auger, Russian corer, Wardenaar corer	M2, M3
			54.9		B-D4**	−1.25 ± 0.00	Sample rings, gouge auger, Russian corer	M2, M3
− 1.30 ± 0.07	*Sphagnum* with cotton grass and some dwarf shrub remains	5	–	Permanently saturated conditions	B-D5**	−1.5 ± 0.00	Gouge auger, Russian corer	M3
< −1.30	*Sphagnum*	7		Permanently saturated conditions				
−4.00	*Sphagnum*	7–8	–	Permanently saturated conditions	B-D6**, B-D7**, B-D8**, B-D9**, B-D10**	−2.0 ± 0.00, −2.5 ± 0.00, −3.0 ± 0.00, −3.5 ± 0.00, −4.0 ± 0.00	Gouge auger, Russian corer	M3

* sampling depths according to horizon boundaries.
**sampling depths according to fixed depth increments.

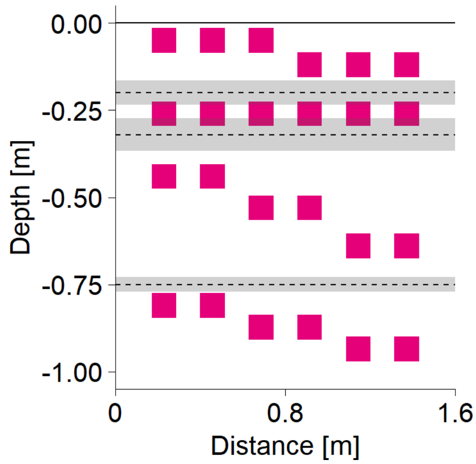

Fig. 1. Schematic illustration of the vertical and horizontal sampling positions of the sample rings at the fen peat site. Dashed lines show the mean horizon depths and the grey areas show the standard deviation of the horizon depth.

The cores of the driving hammer device (sheath probe, Eijkelkamp, Netherlands) were driven into the soil by an electric percussion hammer (Wacker EH 23, Wacker Neuson). During insertion, a polyethylene tube inside the cylinder unrolled around the soil. The cores were extracted using a hydraulic extractor (Eijkelkamp, Netherlands). The total core length and depth of the sample hole were recorded and cores were corrected linearly for compression or stretching. Afterwards, the polyethylene tube was unwrapped and samples were stored in plastic bags. The field setup of the driving hammer device was the same as that referred to as a "sheath probe" by Walter et al. (2016).

For sampling with the gouge auger (Eijkelkamp, Netherlands), the corer was pushed manually into the soil and then rotated in order to excavate the soil. The soil cores were taken at overlapping depths from two parallel holes, i.e. for the depths of 0.1 to 1.1 m from hole 1, 0.9 to 1.9 m from hole 2, 1.7 to 2.7 m from hole 3 etc. (see graphical abstract). From every-one-metre long sample, the first and last 0.1 m were removed to avoid edge effects, leaving a sample with a length of 0.8 m.

The Russian corer was pressed manually into the soil, as well. By rotating the corer, the soil was filled into the chamber and closed in. Details can be found in Belokopytov and Beresnevich (1955) and Jowsey (1966). In contrast to the gouge auger, the samples were not taken from overlapping depths between the two alternating holes since the whole core was taken for analysis as it is considered to be fully undisturbed.

The Wardenaar corer (Eijkelkamp, Netherlands) was pushed into the soil with locked hinges. As soon as the resistance became too great, the hinges were loosened and the two half casings were pushed in turn into the soil. After the corer was inserted 1 m into the soil, it was excavated.

After sampling, every sample was carefully checked for any sign of damage, edge effects or an irregular shape. If in any doubt, sampling was repeated. Sampling could not be performed with all sampling devices in all sampling depths. At sampling depths with the highly decomposed amorphous and aggregated peat (B-D1, F-D1 and F-D2), samples could only be taken with the sample rings and the driving hammer. In greater sampling depths, samples could only be taken with gouge auger and Russian corer. At the fen peat site, no samples could be taken with the Wardenaar corer because the peat was too compacted. Tables 1 and 2 show which sampling devices were used at which sampling depths.

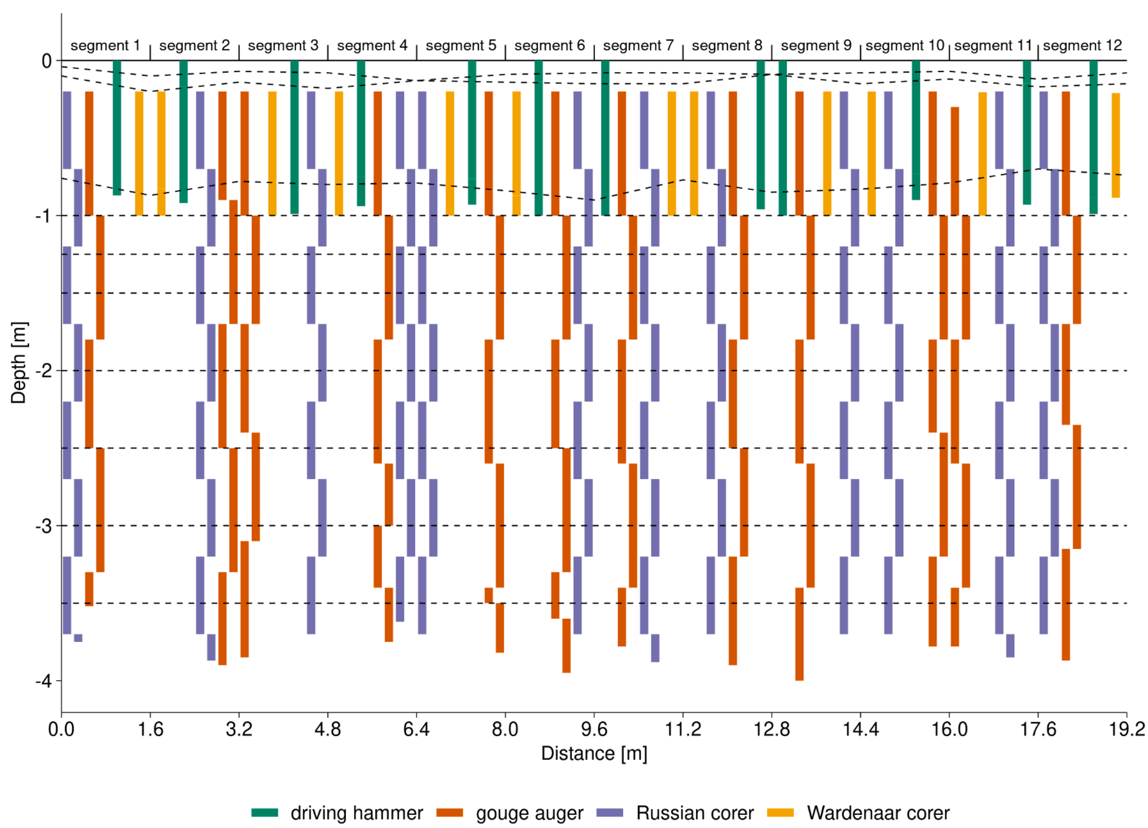

Fig. 2. Sampling positions and depths for the samples taken with the driving hammer, gouge auger, Russian corer and Wardenaar corer from the 12 segments of the bog soil profile. Sampling depths are depicted with dashed lines. They were determined from 0.00 to −1.00 m by the soil horizons and from −1.00 to −3.50 m by fixed depth increments. All samples were taken approximately 0.50 m behind the profile wall. Randomized sampling positions for the four sampling devices in every segment were at a distance of 0.2, 0.6, 1.0 and 1.4 m along the profile wall. Soil cores with a gouge auger and Russian corer were taken from two parallel holes ± 0.1 m from these positions (e.g. at 0.1 m and 0.3 m for the sampling position at 0.2 m etc.).

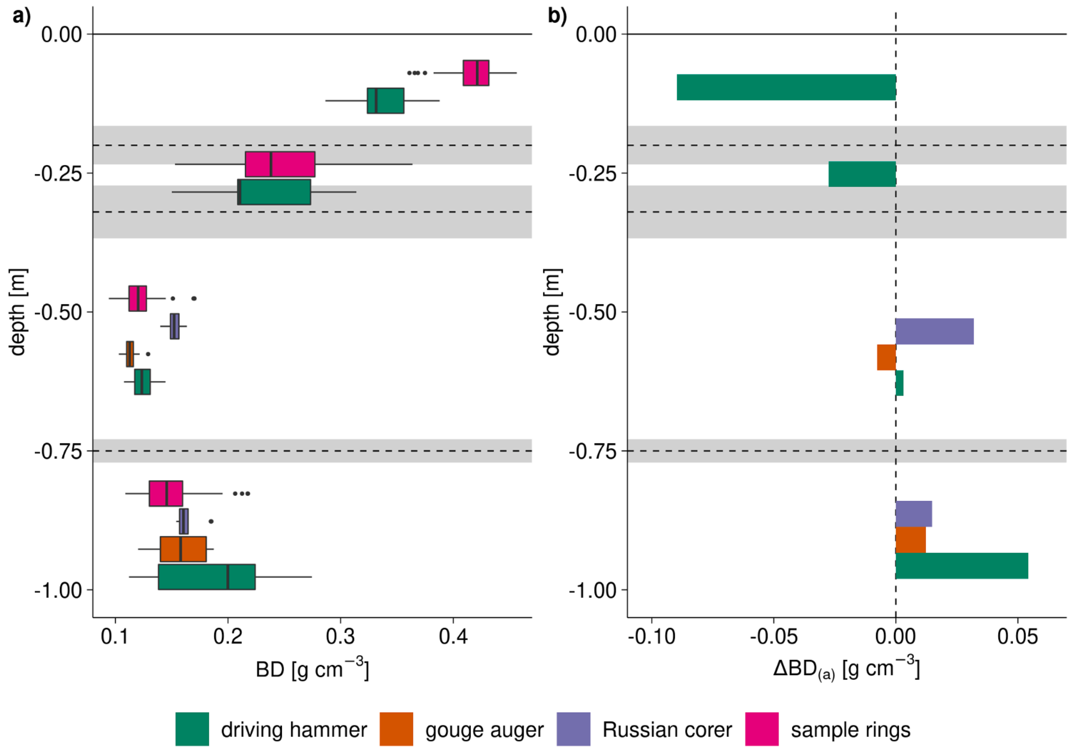

Fig. 3. a) Bulk density (BD) determined with a driving hammer, gouge auger, Russian corer and sample rings (boxes define the 25–75% quartiles, whiskers are 1.5 times the quartile, points represent values outside this interval) and b) difference between BD determined with a driving hammer, gouge auger and Russian corer ($\Delta BD_{(a)}$) and BD using sample rings for sampling depths F-D1, F-D2, F-D3 and F-D4 at the fen peat site. Dashed lines show the sampling depths, in particular the mean value of the horizon boundaries along the soil pit. The grey area is the corresponding standard deviation.

2.4. Data analyses

All the data analyses were performed using the statistical software package R (R Core Team, 2020). The data set comprised 947 BD data points (driving hammer: 84, gouge auger: 131, Russian corer: 132, sample rings: 576, Wardenaar corer: 24): 563 from the bog peat site and 384 from the fen peat site.

Seventeen outliers (driving hammer: 1, gouge auger: 6, Russian corer: 3, sample rings: 7) were identified by visual checks on dot plots and histograms and confirmed by Grubbs' outlier test (Grubbs, 1950). Most of the outliers had components from the underlying mineral soil included and thus substantial higher bulk densities. All outliers were removed from the dataset before further evaluation, resulting in a total of 930 BD values.

2.4.1. Calculating bulk density and total peat mass

After sampling, all the samples were dried at 105 °C for at least 48 h and BD was determined based on standard mass calculation by dividing dry peat mass with sample volume. Dry peat masses [t ha^{-1}] were calculated by multiplying BD by the thickness of the respective sampling depths. Afterwards median values of all segments from the top of the soil profile to the bottom were summed to calculate cumulative peat masses. The gouge auger, Russian corer and Wardenaar corer could not be used for sampling depths in the upper parts of the profiles. This hampers the comparison of total peat masses determined with different coring devices. Hence, peat masses calculated from the sample rings were used for these devices and sampling depths to be able to compare peat masses throughout the entire profile depths.

2.4.2. Statistical analyses of differences in bulk density

Differences in BD values determined with different sampling devices were analysed using linear mixed-effects models (R package nlme, Pinheiro et al., 2020). Sampling devices were set as the fixed effect. As random effects, a combination of site and horizon and the segment of the soil profile were used. As not all sampling devices could be employed for all sampling depths, the statistical analysis of BD was separated into three different linear mixed-effects models (see Table 1 and 2).

The **first model** (M1) was used to analyse differences for the three sampling depths with amorphous and aggregated highly decomposed peat (bog peat site: B-D1; fen peat site: F-D1 and F-D2) from which samples could only be taken with the driving hammer and sample rings. With the **second model** (M2), all sampling depths were analysed that could be sampled with all devices. As an exception, F-D3 and F-D4 of the fen peat site were also included, although the Wardenaar corer could not be used. Furthermore, sampling depth B-D4 at the bog peat site was also included in the model although samples could only be taken with the sample rings, gouge auger and Russian corer. The **third model** (M3) compared the gouge auger with the Russian corer down to the mineral soil, and thus included all sampling depths at which samples were taken with these devices. Analogous to M2, the sampling depths contained slightly to moderately decomposed *Sphagnum* or brown moss peat.

2.4.3. Comprehensive comparison of all sampling devices

Sample rings were used as reference devices for all the other devices at each sampling depth where sample ring samples could be taken (B-D1 to B-D4, F-D1 to F-D4). For a comprehensive comparison of all sampling devices, this study followed Walter et al. (2016) and the mean prediction error (MPE) was determined (Vasiliniuc and Patriche, 2015) as a measure of accuracy (or systematic error or bias) for each sampling device with:

$$MPE = \frac{1}{n} \bullet \sum_{i=1}^{n} (BD_i - BD_{ref}) \quad (1)$$

where BD_{ref} is the median BD determined with the sample rings and BD_i is the BD of the respective sampling device. The random error was assessed by the standard deviation of the prediction error (SDPE)

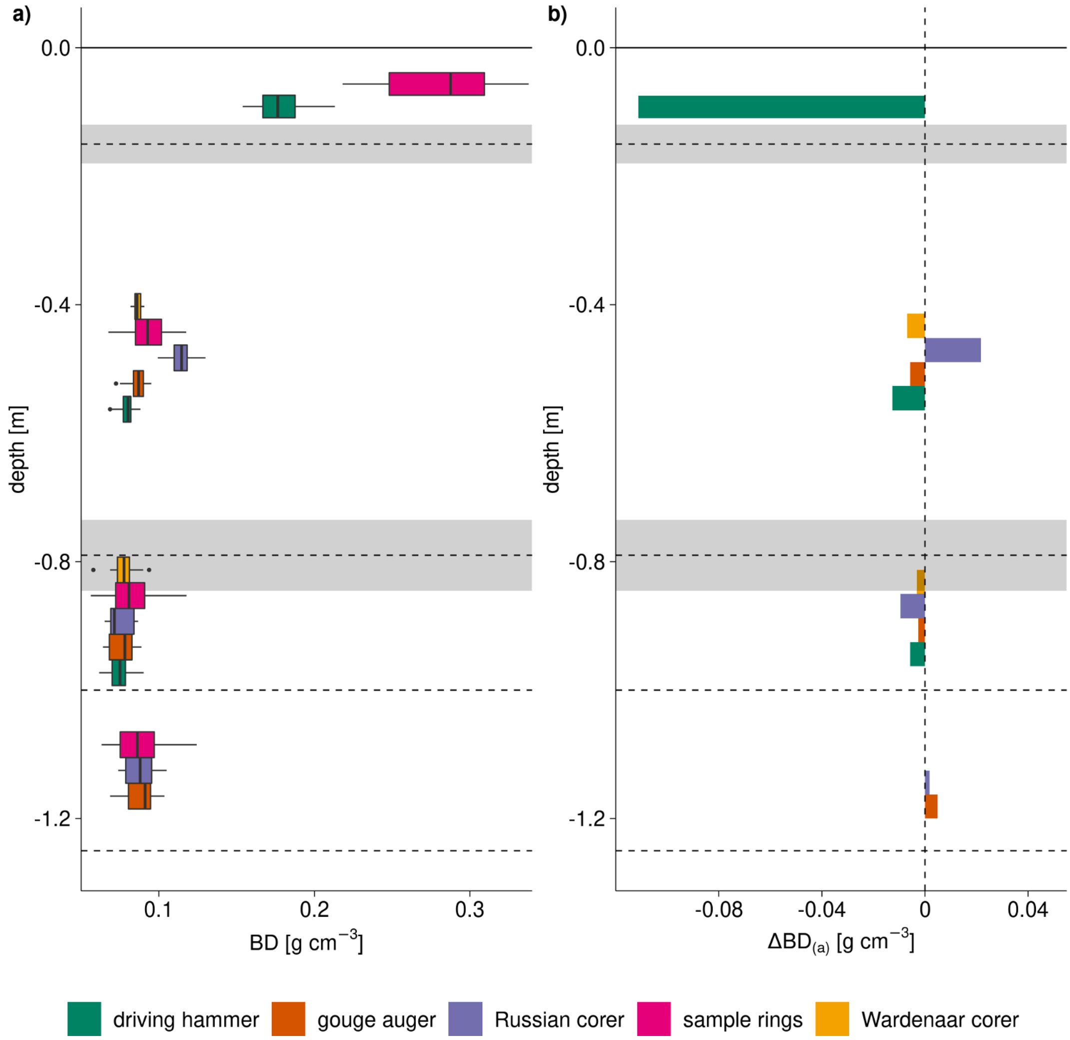

Fig. 4. a) Bulk density (BD) determined with a driving hammer, gouge auger, Russian corer, sample rings and Wardenaar corer (boxes define the 25–75% quartiles, whiskers are 1.5 times the quartile, points represent values outside this interval) and b) difference between BD determined with a driving hammer, gouge auger and Russian corer ($\Delta BD_{(a)}$) and BD using sample rings for sampling depths B-D1, B-D2, B-D3 and B-D4 at the bog peat site. Dashed lines are the sampling depths. The top two dashed lines show the mean value of the horizon boundaries along the soil pit and the grey area is the corresponding standard deviation.

(Vasiliniuc and Patriche, 2015):

$$\mathrm{SDPE} = \sqrt{\frac{1}{n-1}\bullet\sum\nolimits_{i=1}^{n}\left[\left(\mathrm{BD}_i - \mathrm{BD}_{\mathrm{ref}}\right) - MPE\right]^2} \tag{2}$$

Both, MPE and SDPE were calculated for the sampling depths with amorphous and aggregated peat (sample rings and driving hammer) and for the sampling depths with slightly to moderately decomposed peat in which samples were taken with all sampling devices.

3. Results

3.1. Bulk densities

The BD for all sampling devices at sampling depths F-D1, F-D2, F-D3 and F-D4 are shown in Fig. 3a (fen peat site) and at B-D1, B-D2, B-D3 and B-D4 in Fig. 4a (bog peat site). It should be noted that Fig. 4 does not show the BD values for all sampling depths down to the mineral soil. Differences in medians between sample rings with the other sampling devices ($\Delta BD_{(a)}$) are depicted in Figs. 3b and 4b respectively. Negative values mean that the BD of the sampling device was lower than the BD of the sample rings, and positive values indicate the opposite. All results (median values ± standard deviation of sampling devices and sampling depths across the profile segments) can be also found in the appendix (Tables A1 and A2).

At both sites and for all sampling devices, BD values decreased with depth. The fen peat site had higher BD values than the bog peat site.

3.1.1. Sampling amorphous and aggregated peat: sample rings vs driving hammer

In the sampling depths with highly decomposed amorphous and aggregated peat (B-D1, F-D1 and F-D2), BD was only determined with sample rings and a driving hammer (Figs. 3 and 4). It was physically impossible to acquire samples with the other sampling devices from the amorphous and aggregated peat without damaging the devices. The driving hammer samples were slightly compressed or stretched, with core lengths varying from 0.99 m to 1.06 m at the fen peat site and from 0.94 to 1.03 m at the bog peat site. Overall, BD values determined with the driving hammer at these sampling depths were significantly lower (mean difference 0.067 g cm^3, $p < 0.000001$; linear mixed-effects model M1) than BD values determined with sample rings. Differences were the most distinctive at B-D1 ($\Delta BD_{(a)}$: −0.111 g cm^{-3}≙ 39 %) and F-D1 ($\Delta BD_{(a)}$: −0.090 g cm^{-3} ≙ 21 %). At the sampling depth F-D2 differences in BD between sample rings and driving hammer ($\Delta BD_{(a)}$: −0.028 g cm^{-3} ≙ 11 %) were lower than for the two topmost horizons.

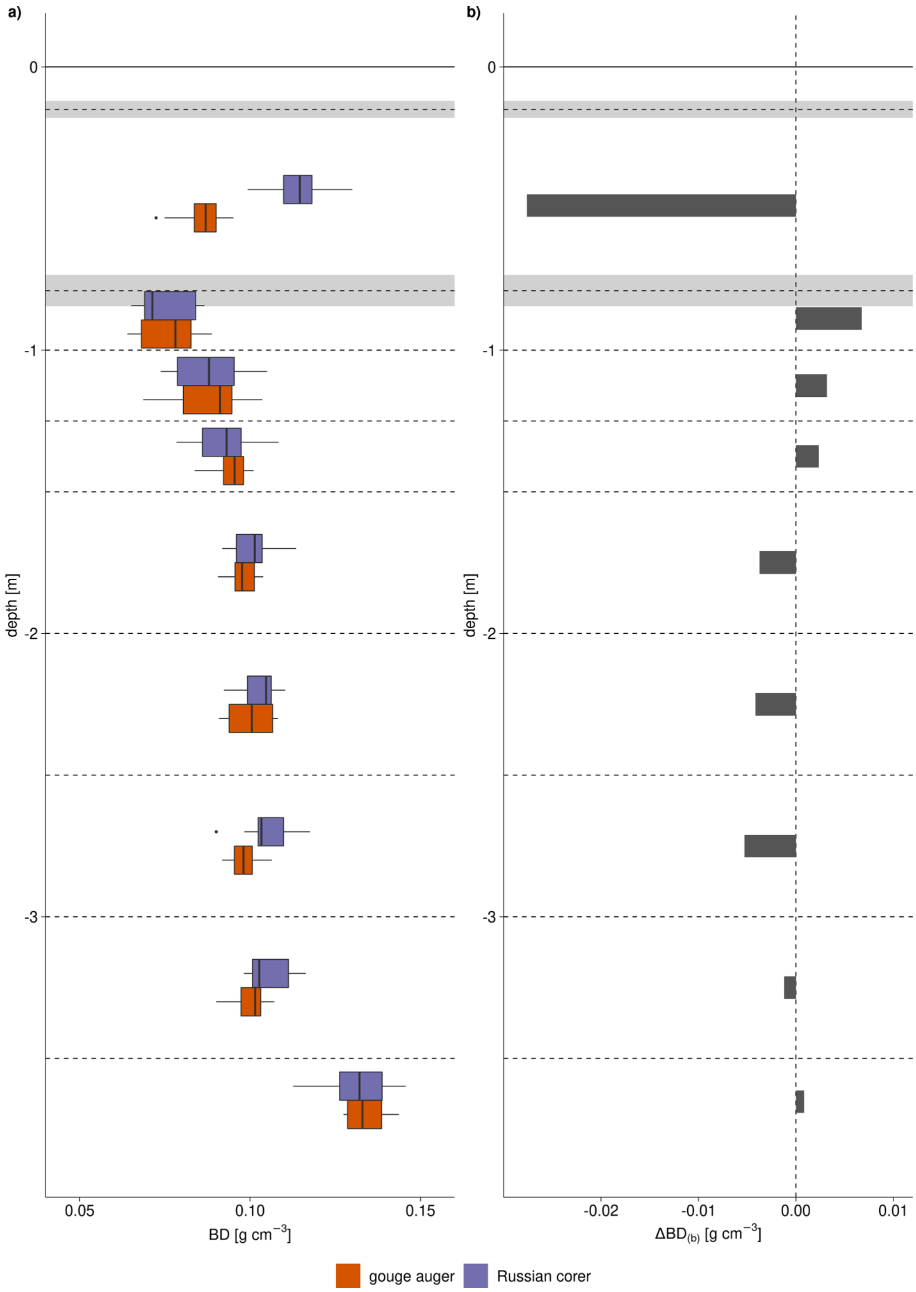

Fig. 5. a) Bulk density (BD) determined with a gouge auger and a Russian corer (boxes define the 25–75% quartile, whiskers are 1.5 times the quartile, points represent values outside this interval) and b) difference between BD determined with a gouge auger and a Russian corer ($\Delta BD_{(b)}$) for sampling depths B-D2 to B-D9 at the bog peat site. Dashed lines are the sampling depths. The top two dashed lines show the mean value of the horizon boundaries along the soil pit and the grey area is the corresponding standard deviation.

3.1.2. Sampling slightly to moderately decomposed peat: a comparison of all devices

A comprehensive comparison of BD determined with all sampling devices could be performed at the fen peat site for F-D3 and F-D4 (Fig. 3) and at the bog peat site for B-D2, B-D3 and B-D4 (Fig. 4) (see also Tables 1 and 2). Please notice that the Wardenaar corer is only shown in Fig. 4 as sampling failed at the fen peat site. Sampling depth B-D4 was below −1 m and thus no BD values for driving hammer or Wardenaar corer could be shown in Fig. 4.

The linear mixed-effects model (M2) showed significant differences between sample rings and the Russian corer ($p < 0.000001$). These differences were the most pronounced for B-D2 (bog peat site) and F-D3 (fen peat site), which were both characterised by alternating saturated–unsaturated conditions (see also Tables 1 and 2). For the underlying permanently saturated sampling depths (B-D3, B-D4 and F-D4), the $\Delta BD_{(a)}$ values of the Russian corer were substantially lower at both sites (Fig. 3b and Fig. 4b). No significant differences between sample rings and driving hammer ($p = 0.0835$) were found, despite a large $\Delta BD_{(a)}$ at F-D4 (Fig. 3b). The gouge auger and Wardenaar corer showed only minor and non-significant differences to the sample rings ($p > 0.4$).

3.1.3. Sampling slightly to moderately decomposed peat: Gouge auger vs Russian corer

At the bog peat site, sampling down to the mineral soil could only be performed with the gouge auger and Russian corer. The corresponding BD values are shown in Fig. 5a. Differences in BD between both devices ($\Delta BD_{(b)}$) (median BD determined with a gouge auger minus median BD determined with a Russian corer) are shown in Fig. 5b. The values of $\Delta BD_{(b)}$ of the fen peat site are not shown separately, but Fig. 3a shows that differences between the two devices were larger under unsaturated conditions (F-D3) than in the permanently saturated sampling depth (F-D4).

The linear mixed-effects model (M3) including both sites and all sampling depths showed a significant difference of 0.008 g cm^{-3} ($p <$

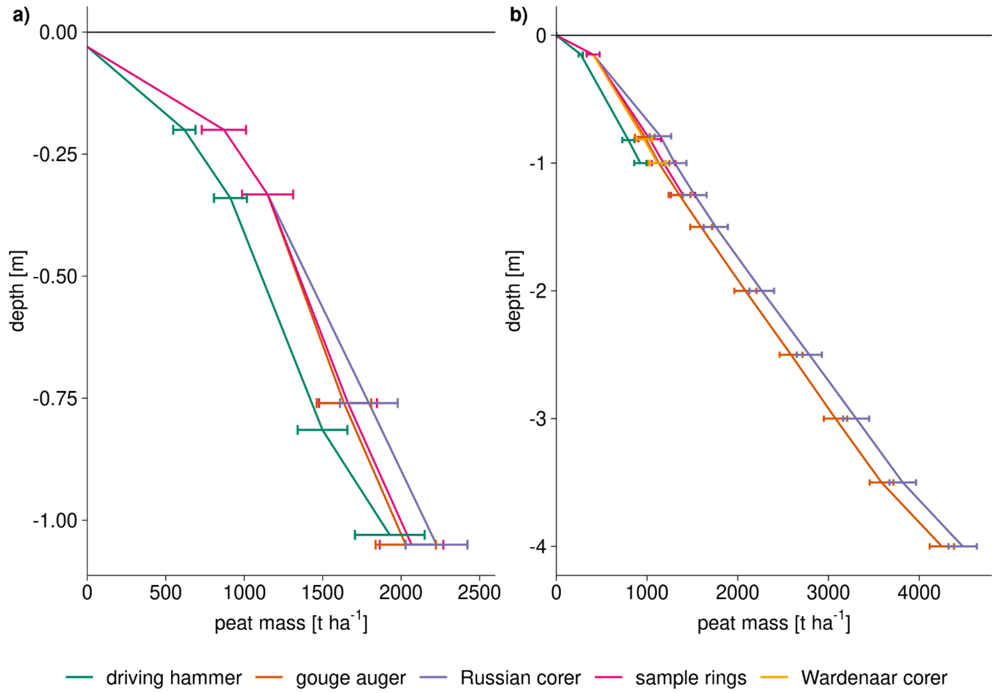

Fig. 6. Cumulative peat masses [t ha^{-1}] from 0 m down to the mineral soil determined with all sampling devices for a) the fen peat site and b) the bog peat site. Values are the median peat masses over all segments. Horizontal lines depict the standard deviations. For the gouge auger, the Russian corer and the Wardenaar corer, peat masses of the first two (fen peat) and first (bog peat) sampling depths were taken from the sample rings.

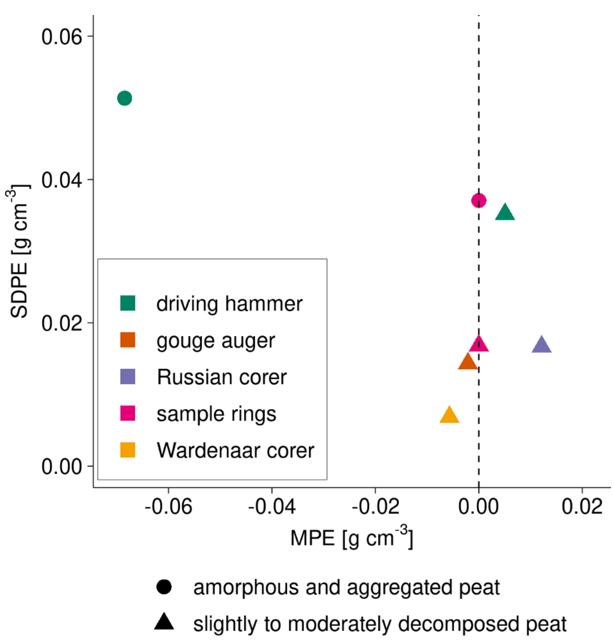

Fig. 7. Mean prediction error [g cm^{-3}] (MPE) and standard deviation of prediction error [g cm^{-3}] (SDPE) of bulk densities determined with all sampling devices separated into sampling depths with amorphous and aggregated peat (B-D1, F-D1 and F-D2) and sampling depths with slightly to moderately decomposed peat (B-D2, B-D3 and B-D4, F-D3 and F-D4). Positive MPE = systematic compaction of the sample.

0.000001) between the two sampling devices. However, with the exception of B-D2 ($\Delta BD_{(b)}$ = −0.028 g cm^{-3}) and F-D3 ($\Delta BD_{(b)}$ = −0.039 g cm^{-3}), all values of $\Delta BD_{(b)}$ were$<$0.01 g cm^{-3}. Those two sampling depths were characterised by alternating unsaturated–saturated conditions and thus were dryer than the other sampling depths considered in M3. For the underlying permanently saturated sampling depths, the differences were less distinctive (e.g. 0.003 g cm^{-3} in F-D4) and the BD values were similar. If the above-mentioned sampling depths with alternating unsaturated–saturated conditions were removed from the linear mixed-effects model, the model predicted non-significant (p = 0.06) differences of 0.002 g cm^{-3} between the two devices.

3.2. Determination of total peat mass

Fig. 6 shows the cumulative peat mass [t ha^{-1}] from 0 cm down to the mineral soil for the fen peat site (Fig. 6a) and the bog peat site (Fig. 6b). Total peat mass is given by the value at peat depth (1.05 and 4.0 m, respectively). The different scales of the y-axis in Fig. 6a and b should be noted. The cumulative peat masses for the gouge auger, Russian corer and Wardenaar corer (which are difficult to distinguish in Fig. 6b as the values were similar to the gouge auger and sample rings) started at sampling depths below the amorphous and aggregated peat using the peat masses calculated from the sample rings for the upper sampling depths. At the fen peat site, cumulative peat masses started at −0.03 m because the extremely densely rooted top layer was removed before sampling.

At the fen peat site, sampling with the driving hammer device resulted in the lowest (1927.4 ± 222.1 t ha^{-1}) peat masses (median ± standard deviation) and sampling with the Russian corer in the highest (2225.4 ± 197.2 t ha^{-1}) peat masses. Peat masses determined with the gouge auger (2029.2 ± 192.5 t ha^{-1}) were similar to those determined with the sample rings (2066.4 ± 202.7 t ha^{-1}). The higher peat masses of the Russian corer were based on the higher values at F-D3 (see also Fig. 3). In the case of the driving hammer probes, the low peat masses in F-D1 and F-D2 were compensated for by the higher values in F-D4, leading to similar total peat masses when considering the complete soil core.

At the bog peat site, total peat masses down to the mineral soil could only be determined with the gouge auger (4249.2 ± 134.4 t ha^{-1}) and Russian corer (4478.8 ± 156.0 t ha^{-1}). As in the case of the fen peat site, the slightly higher peat masses determined with the Russian corer were caused by the higher values determined at the unsaturated sampling depth B-D2 (see also Fig. 4).

Comparing the peat masses determined with all the sampling devices at the bog peat site down to −1 m depth (bottom of B-D3 at −1 m depth), the driving hammer had the lowest values (925.8 ± 68.6 t ha^{-1}) and the Russian corer the highest values (1305.0 ± 128.2 t ha^{-1}). The gouge auger (1129.2 ± 116.7 t ha^{-1}), Wardenaar corer (1114.5 ± 91.3 t ha^{-1}) and sample rings (1181.6 ± 129.2 t ha^{-1}) showed similar values.

3.3. Comprehensive comparison of all sampling devices

Fig. 7 shows a comprehensive comparison of all sampling devices with the sample rings, separated into the sampling depths with amorphous and aggregated peat (sample rings vs driving hammer) and slightly to moderately decomposed *Sphagnum* or brown moss peat (sample rings vs driving hammer, gouge auger, Russian corer and Wardenaar corer) in terms of BD.

In the sampling depths with amorphous and aggregated peat, the driving hammer caused a high systematic error, expressed by a mean prediction error (MPE) differing from zero by 0.068 g cm^{-3}. Both sampling devices had a high random error with a standard deviation of the mean prediction error (SDPE) of 0.051 g cm^{-3} (driving hammer) and 0.037 g cm^{-3} (sample rings). This can also be seen in the high variances of BD at F-D1 (Fig. 3a), F-D2 (Fig. 3a) and B-D1 (Fig. 4a).

In contrast, at the sampling depths with slightly to moderately decomposed peat, the systematic error was generally low. Bulk density determined with the gouge auger (MPE: −0.002 g cm^{-3}) had the smallest difference from BD determined using the sample rings, followed by the driving hammer (MPE: 0.005 g cm^{-3}) and the Wardenaar corer (MPE: −0.006 g cm^{-3}). The largest systematic error was determined for the Russian corer (MPE: 0.012 g cm^{-3}). For both the sample rings and driving hammer, the random errors of the derived BD values were lower than those determined for amorphous and aggregated peat samples. The driving hammer had the highest SDPE with 0.035 g cm^{-3} and the Wardenaar corer the lowest with 0.007 g cm^{-3}. The random errors of the gouge auger (0.014 g cm^{-3}), Russian corer (0.017 g cm^{-3}) and sample rings (0.017 g cm^{-3}) were within a similar range.

4. Discussion

4.1. Volume-based sampling of peat with differing properties

4.1.1. Highly decomposed amorphous and aggregated peat

The results showed that reliable volume-based sampling of amorphous and aggregated peat in the unsaturated zone was only possible with sample rings. For the gouge auger, Russian corer and Wardenaar corer, the peat was either too crumbly, dusty or small-grained for sampling and/or too hard to drive the coring device (especially Wardenaar corer) into the peat. Sampling with the driving hammer device was technically possible, but failed to provide BD values with acceptable precision and accuracy as it showed a larger random error than sample rings and a strong bias. The median BD values at the three sampling depths concerned were underestimated by 39 %, 21 % and 12 %. Although even an underestimation of 12 % of the median BD value is large, it should be noted that the 25–75 % quartiles of BD in this particular sampling depth (F-D2) were within the same range (Fig. 3a). The underestimations at both sites could have been caused by the shaking driving hammer loosening the topsoil before the sampling device could be driven into the soil. Walter et al. (2016) compared BD values of peat soils sampled with sample rings and the same driving hammer device used in the present study and found good agreement in the first depth increment. In the second depth increment, the BD values determined with the driving hammer were also underestimated by 18 % (0.09 g cm^{-3}). However, these two depth increments might not be comparable with the sampling depths with amorphous peat in the present study as sampling took place under different soil moisture conditions. Furthermore, the aggregates at the fen peat site were particularly well developed and rigid, which might be the reason for both the difference between the sampling devices and the high variability in the sample ring and driving hammer BD data (Fig. 3a). Thus, the conditions might be considered “worst case” and the problems encountered in the unsaturated zone might turn out to be less severe elsewhere.

At the fen peat site, the $\Delta BD_{(a)} < 0$ in the upper sampling depths (F-D1 and F-D2) and the $\Delta BD_{(a)} > 0$ values in the lower sampling depths (F-D3 and F-D4) indicated that the lower part of the soil core was compressed and the upper part was stretched when using the driving hammer. However, this nonlinear compression and stretching could not be quantified. At the bog peat site, only speculations could be made about the large underestimations of BD in the amorphous sampling depths as the $\Delta BD_{(a)}$ values were below zero across the entire length of the soil core.

4.1.2. Slightly to moderately decomposed Sphagnum and brown moss peat

Overall, all the sampling devices could be used to sample the *Sphagnum* peat and brown moss peat (with the exception of the latter with the Wardenaar corer). The systematic errors were either lower or in the range of the systematic errors of Walter et al. (2016). The random error of the Wardenaar corer was lowest in this study, which was probably due to the large sample volume compared with the other sampling devices. Random errors of the sample rings, the Russian corer and the gouge auger were slightly higher and similar to each other, but those of the driving hammer were twice as high. This error does not only comprise (random) differences in handling the devices, but also the well-known small-scale variability of the peat properties. However, as all corers were used in all segments, the differences in random errors should be independent of any differences in peat properties (e.g. non-occurrence of a horizon in some segments).

For slightly to moderately decomposed *Sphagnum* or brown moss peat, the driving hammer device showed good results, except for sampling depth F-D4, where BD values were increased possibly by compression. This can only be the subject of speculation, but compression might have been enhanced by the underlying mineral substrate preventing the peat soil from being pushed deeper by the front of the sheath core of the driving hammer device.

The gouge auger was the sampling device with the lowest systematic error (MPE = −0.002 g cm^{-3}) compared with the sample rings. Bulk density values determined from samples taken with the Russian corer agreed well with those of the gouge auger and sample rings, except for the unsaturated sampling depths (F-D3 and B-D2) where the Russian corer caused significantly higher BD values. This was probably an effect of compression of the soil in the sampling chamber, as unsaturated soil is more compressible than saturated peat (Hobbs, 1986). Another study also reported compression by the Russian corer when it is used to sample the acrotelm (the temporarily unsaturated and very loose zone of an intact mire) but not when used for peat soils from greater depths (De Vleeschouwer et al., 2010). Wardenaar (1987) also reported sampling above the water table to be difficult with the Russian corer.

Bulk density values determined from samples taken with the Wardenaar corer showed good agreement with the sample rings, but were slightly, but systematically lower. This was in line with expectations as it was assumed that the Wardenaar corer would be the device which causes least compression as it has the lowest ratio between the sampling device wall and sample volume. However, the low systematic error (MPE = −0.005 g cm^{-3}) showed that samples taken by sample rings were only slightly compressed. At the fen peat site, it was impossible to push the Wardenaar corer into the peat without damaging the device due to the higher BD values and strong aggregation. Accordingly, sampling with the Wardenaar corer was limited to an upper BD threshold between approximately 0.09 and 0.24 g cm^{-3}, at least under unsaturated conditions.

4.2. Determination of total peat mass over the whole peat profile

At the fen peat site, it was possible to determine total peat masses over the whole peat profile down to the mineral soil with two of the sampling devices without having to change devices for different depths. Both the driving hammer and sample rings led to similar total peat masses, but with differences at the different sampling depths. When using the other devices, total peat masses could only be determined by combining sampling devices, i.e. the gouge auger and Russian corer could not sample the amorphous and aggregated peat, for which sample rings needed to be used in order to determine total peat masses.

At the bog peat site, total peat masses could only be determined using either the gouge auger or the Russian corer in combination with sample rings for the topmost sampling depth. Combining different coring devices to sample the total peat profile requires the results obtained by these devices to be not significantly different. However, in many cases it is the only possibility for sampling all soil horizons or layers and thus is common practice (e.g. in De Vleeschouwer et al., 2010 or Wellock et al., 2011). Here, it could clearly be shown that BD data obtained from the gouge auger was indistinguishable from the values determined with sample rings for slightly to moderately decomposed peat, even under unsaturated conditions. The same is true for the Russian corer under saturated conditions, where the BD differences to the gouge auger were very small.

4.3. Choice of sampling device

Our results highlight the challenges and complexities which need to be considered for a reliable volume-based sampling of peat soils. It is clearly demonstrated that several sampling devices are needed to cover various field conditions (e.g. peat properties, moisture conditions, depth of the peat profile). However, if an appropriate choice of the sampling device is made and samples are checked carefully for any signs of damage, volume-based sampling with high accuracies and low systematic errors is possible when combining different sampling devices, both within one peat profile and across sites. To achieve this, following points should be considered:

- For a horizon or layer wise determination of BD in amorphous and/or aggregated peat soils, sample rings are the only choice for reliable volume-based sampling. The driving hammer device is not a good option as shown by the large random and systematic errors. It will, however, be an appropriate choice at sites with shallow peat, if BD or peat masses need to be determined for the whole peat profile only, but not for individual layers or horizons. For this purpose, it is essential that the length of the soil core is greater than the peat thickness.
- The Wardenaar corer and the gouge auger will always be a good choice if sampling is possible under the given field conditions. This is clearly shown by the low systematic and random errors. This also applies to the Russian corer for saturated peat. For unsaturated peat layers or horizons, we would not recommend the Russian corer as results showed an overestimation of BD in these sampling depths.
- For deep peat soils, gouge auger and Russian corer are the only options, but both are a good choice. If it proves to be impossible to reliably sample some horizons or soil layers within the profile, they can be unhesitatingly be combined with other sampling devices (e.g. sample rings or Wardenaar corer) in order to determine the peat mass over the entire profile.

We want to stress that our findings are based on the soil properties of the two sites of this study. They are not necessarily covering the high variety of different peatlands and peat soils in general. Thus, we cannot exclude the possibility that field conditions exist, where other sampling strategies and choices of sampling devices will become necessary.

5. Conclusions

This study shows for the first time that BD values obtained with different sampling devices are not significantly different from the data from sample rings given the conditions outlined here are met. This is highly relevant for designing sampling and monitoring programmes, as the results clearly demonstrate that there is not a “one-size-fits-all” solution for volume-based sampling of the whole profile of deep peat soils and that in profiles with deep peat soils and amorphous or aggregated unsaturated horizons, sample rings need to be combined with other sampling devices to reliably determine the peat (and thus SOC) mass over the entire profile. Finally, the choice of sampling device should depend on the depth of the peat profile, the properties of the peat (moisture states, degree of decomposition and of secondary pedogenetic transformation) and whether BD needs to be determined for horizons, depth increments or across the entire peat profile. Overall, the results of the study may be used to obtain high-quality data sets of stocks of SOC (and other substances). Such data is required for targeting and evaluating mitigation measures, but also to improve regionalisation approaches based on modelling or remote sensing approaches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We would like to express our sincere thanks to the two farmers, Bernhard Grabau and Steffen Imbusch, who shared their land with us and made the study possible. We are grateful to Sonia Antonazzo, Frank Hegewald, Arne Heidkamp, Sebastian Heller, Tina Lages, Sebastian Willi Oehmke, Adina Schlegel, Claas Voigt, Sarah Fiedler and Greta Richers for their support in the field. We appreciate the laboratory assistance of Lena Lüttjohann and Maria Schmitt. We also thank Axel Don for his comments on the study design. This study is part of the project ‘Establishment of a German peatland monitoring programme for climate protection. Part 1 - Open land’ funded by the German Federal Ministry of Food and Agriculture.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.116132.

References

Agus, F., Hairiah, K., Mulyani, A., 2011. Measuring carbon stock in peat soils: practical guidelines. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. Indonesian Centre for Agricultural Land Resources Research and Development 60p.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47 (2), 151–163. https://doi.org/10.1111/j.1365-2389.1996.tb01386.x.

Belokopytov, I., Beresnevich, V., 1955. Giktorf's peat borers. Torfyanaya Promyshlennost 8, 9–10.

Blake, G.R. and Hartge, K.H. 1986. Bulk Density. In: Klute, A. (ed): Methods of Soil Analysis. 363-375. doi: https://doi.org/10.2136/sssabookser5.1.2ed.c13.

Boden, A.-H.-AG., 2005. Bodenkundliche Kartieranleitung (Soil survey manual). Bundesanstalt für Geowissenschaften und Rohstoffe in Zusammenarbeit mit den Staatlichen Geologischen Diensten. der Bundesrepublik Deutschland, Hannover.

Chimner, R.A., Ott, C.A., Perry, C.H., Kolka, R.K., 2014. Developing and Evaluating Rapid Field Methods to Estimate Peat Carbon. Wetlands 34 (6), 1241–1246. https://doi.org/10.1007/s13157-014-0574-6.

De Vleeschouwer, F., Chambers, F.M., Swindles, G.T., 2010. Coring and sub-sampling of peatlands for palaeoenvironmental research. Mire Peat 7 (1), 1–10.

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

du Rietz, G.E., 1954. Die Mineralbodenwasserzeigergrenze als Grundlage einer natürlichen Zweigliederung der nord-und mitteleuropäischen Moore. Veg. Acta Geobot. 5(1), 571–585. https://doi.org/10.1007/BF00299611.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75 (4), 529–538. https://doi.org/10.4141/cjss95-075.

DIN EN ISO 11272, 2001. Soil quality – Determination of dry bulk density. Beuth Verlag GmbH, Germany.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. Environ. Rev. 19, 371–396. https://doi.org/10.1139/a11-014.

Gorham, E., 1957. The development of peat lands. Q. Rev. Biol. 32 (2), 145–166.

Grubbs, F.E., 1950. Sample criteria for testing outlying observations. Ann. Math. Stat. 21 (1), 27–58.

Günther, A., Barthelmes, A., Huth, V., Joosten, H., Jurasinski, G., Koebsch, F., Couwenberg, J., 2020. Prompt rewetting of drained peatlands reduces climate warming despite methane emissions. Nat. Commun. 11 (1), 1644. https://doi.org/10.1038/s41467-020-15499-z.

Hobbs, N.B., 1986. Mire morphology and the properties and behaviour of some British and foreign peats. Q. J. Eng. Geol. Hydrogeol. 19 (1), 7–80. https://doi.org/10.1144/GSL.QJEG.1986.019.01.02.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106, Rome: FAO.

Jowsey, P.C., 1966. An improved peat sampler. New Phytol. 65 (2), 245–248. https://doi.org/10.1111/j.1469-8137.1966.tb06356.x.

Leifeld, J., Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nat. Commun. 9 (1), 1071. https://doi.org/10.1038/s41467-018-03406-6.

Leifeld, J., Wüst-Galley, C., Page, S., 2019. Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. Nat. Clim. Change 9 (12), 945–947. https://doi.org/10.1038/s41558-019-0615-5.

O'Kelly, B.C., Pichan, S.P., 2013. Effects of decomposition on the compressibility of fibrous peat — A review. Geomech. Geoeng. 8 (4), 286–296. https://doi.org/10.1080/17486025.2013.804210.

Okruszko, H., Ilnicki, P., 2002. The moorsh horizons as quality indicators of reclaimed organic soils. In: Parent, L.-.-E., Ilnicki, P. (Eds.), Organic Soils and Peat Materials for Sustainable Agriculture. CRC Press LLC, Boca Raton, USA, pp. 1–14.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. and Team, R.C. 2020. _nlme: Linear and Nonlinear Mixed Effects Models_. R package version 3.1-147, URL: https://CRAN.R-project.org/package=nlme.

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org/.

Schrumpf, M., Schulze, E.D., Kaiser, K., Schumacher, J., 2011. How accurately can soil organic carbon stocks and stock changes be quantified by soil inventories? Biogeosciences 8 (5), 1193–1212. https://doi.org/10.5194/bg-8-1193-2011.

Shotyk, W., Noernberg, T., 2020. Sampling, handling, and preparation of peat cores from bogs: review of recent progress and perspectives for trace element research. Can. J. Soil Sci. 100 (4), 363–380.

Simola, H., Pitkänen, A., Turunen, J., 2012. Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. Eur. J. Soil Sci. 63 (6), 798–807. https://doi.org/10.1111/j.1365-2389.2012.01499.x.

Tubiello, F.N., Biancalani, R., Salvatore, M., Rossi, S., Conchedda, G., 2016. A Worldwide Assessment of Greenhouse Gas Emissions from Drained Organic Soils. Sustainability 8 (4), 371. https://doi.org/10.3390/su8040371.

Vasiliniuc, I., Patriche, C.V., 2015. Validating soil bulk density pedotransfer functions using a Romanian dataset. Carpathian J. Earth Environ. Sci. 10 (2), 226–236.

von Post, L., 1922. Sveriges Geologiska Undersöknings torvinventering och några av dess hittills vunna resultat. Sven. Mooskulturföreningens Tidskr 1–27.

Walter, K., Don, A., Tiemeyer, B., Freibauer, A., 2016. Determining Soil Bulk Density for Carbon Stock Calculations: A Systematic Method Comparison. Soil Sci. Soc. Am. J. 80 (3), 579–591. https://doi.org/10.2136/sssaj2015.11.0407.

Wardenaar, E., 1987. A new hand tool for cutting peat profiles. Can. J. Bot. 65 (8), 1772–1773. https://doi.org/10.1139/b87-243.

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

Wittnebel, M., Tiemeyer, B., Dettmann, U., 2021. Peat and other organic soils under agricultural use in Germany: Properties and challenges for classification. Mire Peat 27 (19), 1–24. https://doi.org/10.19189/MaP.2020.SJ.StA.2093.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J., 2010. Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. 37 (13), n/a–n/a.

Zaccone, C., Plaza, C., Ciavatta, C., Miano, T.M., Shotyk, W., 2018. Advances in the determination of humification degree in peat since Achard (1786): Applications in geochemical and paleoenvironmental studies. Earth-Sci. Rev. 185, 163–178. https://doi.org/10.1016/j.earscirev.2018.05.017.