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REVIEW

Reviewing and analyzing shrinkage of peat and other organic soils in relation to selected soil properties

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Abstract

Peat and other organic soils (e.g., organo-mineral soils) show distinctive volume changes through desiccation and wetting. Important processes behind volume changes are shrinkage and swelling. There is a long history of studies on shrinkage which were conducted under different schemes for soil descriptions, nomenclatures and parameters, measurement approaches, and terminologies. To date, these studies have not been harmonized in order to compare or predict shrinkage from different soil properties, for example, bulk density or substrate composition. This, however, is necessary to prevent biases in the determination of volume-based soil properties or for the interpretation of elevation measurements in peatlands, in order to predict carbon dioxide emissions or uptake caused by microbial decomposition or peat formation. This study gives a comprehensive overview of shrinkage studies carried out in the last 100 years. Terminology and approaches are systematically classified. In part I, the concepts for shrinkage characteristics, measurement methods, and model approaches are summarized. Part II is a meta-analysis of shrinkage studies on peat and other organic soils amended by own measurement data obtained by a three-dimensional structured light scanner. The results show that maximum shrinkage has a wide range from 11% to 93% and is strongly affected by common soil properties (botanical composition, degree of decomposition, soil organic carbon, and bulk density). Showing a stronger correlation, bulk density was a better predictor than soil organic carbon, but maximum shrinkage showed a large spread over all types of peat and other organic soils and ranges of bulk density and soil organic carbon.

1 | INTRODUCTION

Peat and other organic soils, for example, some types of gyttja (limnic sediments) or organo-mineral soils, are characterized and defined by their large amount of soil organic carbon (SOC). Exact definitions of peat and organic soils vary between disciplines and traditions (Huang et al., 2009; Wittnebel et al., 2021), but all have in common that a high amount of SOC or soil organic matter (SOM) and the thickness of the profile are major criteria. In this study, peat soils are defined by the SOM content (≥30%) following the German soil classification scheme (Ad-hoc-AG Boden, 2005). The thickness criterion is neglected, as we work with

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Abbreviations: AC, ash content; AWC, available water capacity; LOI, loss on ignition; RMSE, root-mean-square error; SOC, soil organic carbon; SOM, soil organic matter; SSC, soil shrinkage characteristic; TIC, total inorganic carbon; WFPS, water filled pore-space.

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samples from specific horizons. Soils with SOM contents between 15% and 30% were classified as organo-mineral. For simplification, we will refer to both as "organic soils." The large amount of SOM infers unique soil properties (Hobbs, 1986; Ilnicki, 1967), for example, low bulk densities (ρ_b) and high porosities (up to 98%) (Dettmann et al., 2019; Wittnebel et al., 2021). In contrast to mineral soils, remains of peat-forming plants such as peat mosses or sedges are the main constituent of the soil. Therefore, soil properties are, among other factors, determined by the botanical composition and the degree of decomposition, that is, on how much of the original plant material has been broken down to more amorphous organic matter. Organic soils thus show complex and flexible pore structures (McCarter et al., 2020), resulting in changes of the soil volumes on a short- and a long-term basis. These volume changes are driven by changes in pressure heads, soil moisture conditions, and water level (Burghardt & Ilnicki, 1978; Illner, 1982; Liu et al., 2020).

It is very important to consider these volume changes, that is, shrinkage and swelling, for the correct determination and interpretation of any volume-based soil properties, for example, volumetric water content (θ_v), water filled pore-space (WFPS), and ρ_b. This also affects water retention characteristics (Horn et al., 2014; Oleszczuk et al., 2000; Schwärzel et al., 2002; Szatylowicz et al., 1996) and derived values like SOC stocks or available water capacity (AWC). If θ_v is related to the volume at saturation for the whole water retention characteristic curve, the water content at the dry range will be underestimated and characteristic values (e.g., AWC) could be derived incorrectly, leading, for example, to an overestimation of AWC.

On field scale shrinkage, together with the decomposition of organic matter leads to surface motion, that is, changes in surface elevation, which can be observed in peatlands worldwide (Evans et al., 2021; Mirza & Irwin, 1964; Prytz, 1932).

Surface motion is caused by a combination of different physical and biological processes. In pristine and near-natural peatlands, the most relevant processes can be separated into shrinkage and swelling (both physical) and mineralization and net primary production (both biological). On a short-term basis, the physical processes are dominating surface motion, providing the ecosystems with a self-regulation function by keeping the peatland surface close to the water table ("bog breathing," Ingram, 1983; Morton & Heinemeyer, 2019). The relevance of biological processes for surface motion is increasing on a longer time scale (decades to millennia), leading to increasing surface heights by peat formation as long as net primary production is higher than losses of organic matter by mineralization and fluvial export (Clymo, 1984).

In drained peatlands, increased oxygen availability strongly enhances mineralization, leading to high emissions of carbon dioxide (CO_2) (Hiraishi et al., 2014) of up to more than 60 ton CO_2 ha^{-1} year^{-1} (Tiemeyer et al., 2016). Furthermore, additional physical processes contribute to surface motion. The overall loss of surface height due to lower water levels and moisture contents is called "subsidence" and results from the combination of physical (shrinkage, settlement, consolidation, erosion, and compaction), biological (mineralization), and chemical (combustion) processes (Stephens & Speir, 1969). During the first one or two decades after initial drainage, settlement and consolidation are the most important processes leading to high subsidence rates of, for example, 1 cm year^{-1} (Alshammari et al., 2018) or 26 cm year^{-1} (Ilnicki & Eggelsmann, 1977). After the initial settlement and consolidation, the share of mineralization increases with subsidence rates between approximately 0.2 cm year^{-1} (Alshammari et al., 2018) and 3 cm year^{-1} (Ilnicki & Eggelsmann, 1977) depending on drainage depths, climate, land-use, and time since drainage. On a short time-scale, shrinkage and swelling are the major physical processes and will lead to surface motion depending on water table and soil moisture also in drained organic soils.

In both pristine and drained peatlands, measurements of changes in surface heights, that is, of subsidence, are used as a proxy for CO_2 uptake or emissions (Rojstaczer & Deverel, 1993; van den Akker et al., 2008). On long time scales, shrinkage and swelling might be relatively balanced, but on typical project time scales, physical processes add considerable noise to time series of surface height. As physical processes do not contribute to CO_2 fluxes, an understanding of the contribution of these processes to subsidence data is crucial to avoid misinterpretation of, for example, effects of water management. This is especially relevant for the major physical process, that is, shrinkage, and its drivers (e.g., pressure heads, soil moisture, and water table depth), which are needed to disentangle the biological and physical share of surface motion.

Core Ideas

- Shrinkage characteristics of organic and mineral soils differ strongly.
- Shrinkage of organic soils depends on botanical composition, degree of decomposition, and pedogenetic modification.
- Maximum shrinkage of organic soil varied between 11% and 93%.
- For all types of organic soil, bulk density was more suitable to explain maximum shrinkage than SOC.
- Neglecting shrinkage biases the determination of volume-based soil properties (e.g., bulk density and porosity).

Accordingly, an often-studied physical process affecting surface motion is shrinkage. Shrinkage is the volume reduction of a soil due to desiccation. By the withdrawal of pore water, concave menisci develop inside the soil matrix. The corresponding tension forces (surface and interfacial tension) lead to the reduction of pore-space and consequently to the reduction of soil volume (Schothorst, 1977; Stegmann & Zeitz, 2012) accompanied by an increase of ρ_b. In case of strong desiccation, cracks can occur. In pristine and near-natural peatlands with usually high soil moisture levels, shrinkage can be assumed to be reversible (Howie & Hebda, 2018; Oleszczuk & Brandyk, 2008). As shrinkage depends on pressure heads, it is most pronounced in that parts of the peat profile where the largest moisture differences between dry and wet periods occur. Long-term changes of hydrological conditions as massively induced by drainage, for example, agriculture or forestry, or climate change led to a permanently lowered water table and stronger fluctuations of soil moisture in the upper part of the soil profile. As a result, the upper peat horizons are shrinking irreversible, which, in combination with microbial modification of the organic matter leads to secondary pedogenetic processes such as the formation of aggregates (Ilnicki & Zeitz, 2003). As a consequence, the shrinkage and swelling potential of these upper horizons is reduced. However, shrinkage of soil horizons around the new, lowered water table can be assumed to be reversible again (Michel et al., 2004). The partitioning into reversible and irreversible shrinkage and the magnitude of both depends on the composition of the peat, the degree of decomposition and on the frequency and magnitude of previous drying-wetting cycles (Illner, 1982; Ilnicki, 1967; Oleszczuk & Brandyk, 2008).

Shrinkage is not a phenomenon exclusive to organic soils, but also occurs in mineral soils containing clay. Since this is relevant to various aspects of human activities (agriculture, civil engineering etc.), there is a multitude of studies on it. Although we focus on organic soils here, this experience especially regarding measurement methods and modeling approaches is helpful and will thus be included, even though the properties of these two soil groups differ strongly.

Due to the long history of shrinkage measurements and a variety of participating disciplines (e.g., civil engineering, agriculture, peat extraction, and soil and forest science) there were and are different research objectives and scientific and technical opportunities which lead to a variety of approaches how to measure shrinkage and to relate it to any kind of soil properties. As there are many different national or international, historical or recent schemes for soil description and determination of soil properties with different nomenclatures and parameters, results of shrinkage studies are not directly comparable in many cases, and there is no overall consensus which soil properties are crucial for shrinkage. Further, as a concise overview is so far missing, approaches and terminology might be perceived as confusing.

This paper gives a comprehensive overview of shrinkage studies carried out in the last 100 years. Due to the heterogeneity of the disciplines, methods and aims of shrinkage studies, we aim to systematically classify and summarize terminology and approaches. Thus, the first part is a literature review summarizing concepts for shrinkage characteristics, measurement methods, and model approaches. The second part is a meta-analysis of shrinkage studies on organic soils amended by own measurement data. In this study, we aim to clarify the influence of widely available properties of organic soils (botanical composition, degree of decomposition, SOC, and ρ_b) on maximum shrinkage ($S_{\max}$).

2 | PART I: LITERATURE REVIEW ON SHRINKAGE

To find shrinkage related studies we searched google scholar (https://scholar.google.com/) and ISI Web of Science (https://www.webofscience.com/) for the terms "shrinkage," "subsidence," "bog breathing," "mire breathing," "surface oscillation," "Schrumpfung," "Mooratmung," and "Sackung." Further studies were found by tracing citations of previously found studies. As, in this study, shrinkage is meant to be the three-dimensional (3D) volume reduction, we do not consider studies which only measured one-dimensional linear shrinkage, even though this process can be relevant in some cases, especially in civil engineering. Further, we excluded field studies as shrinkage cannot be distinguished from other processes under field conditions. Overall, we found 239 studies about shrinkage of organic and mineral soils and subsidence of organic soils. Of these studies 87 were about shrinkage, 41 dealt with organic soils, and 28 provided data from shrinkage measurements. Those studies are listed in Table 1, with information on the applied methods, materials, and models which are subject of the following three sections. Studies which are used for the meta-analysis in part II of the present study are marked with the number of data points they contributed.

To ensure comparability and evaluability, the data from the identified studies had to fulfill following criteria to be included into the meta-analysis: (1) samples needed to be defined as peat or other organic soils (SOC >7.5%), (2) data were not aggregated too much (e.g., over a wide range of degrees of decomposition) to enable a meaningful classification, (3) samples were dried at least at 80°C to ensure complete desiccation which is important for the correct determination of dry volume (V_{ovendry}) and of ρ_b (Dettmann et al., 2021), (4) samples needed to be intact and not disturbed, and (5) given values of the SOC content needed to be plausible (<60%). Therefore, 15 out of the 28 studies were excluded from meta-analysis (see Table S1 for details). Studies on mineral soils

TABLE 1 Shrinkage studies on organic soils.

Study	Method V	Method for desiccation	Sample type/size	Shrinkage phases	Model	*n*
Eiselen (1802)	*m*	*Evaporation*	Intact cuboids ($V \approx 4800\ cm^3$)	-	-	
Haines (1923)	hg	Evaporation	Disturbed cuboids ($\mathrm{V} \approx 6\ \mathrm{cm}^3$)	Normal, residual[a]	-	
Luikov (1935)	w-p	Heated drier	Cubes ($\mathrm{V} = 91\ \mathrm{cm}^3$)	-	Cubic	
van Dijk and Boekel (1965)	m and gb	Evaporation	Intact cores ($\mathrm{V} = 98\ \mathrm{cm}^3$)	Near-, sub-, supernormal[b]	-	1
Ilnicki (1967)	m	Evaporation and oven (105˚C)	Intact cores ($\mathrm{V} = 250\ \mathrm{cm}^3$)	Near-, sub-, supernormal[b]	-	235
Galvin (1976)	s	Evaporation	Intact cores	-	-	
Illner (1982)	*m*	*Evaporation*	Intact clods ($V = 100\ \mathrm{cm}^3$)	-	-	
Päivänen (1982)	m and s	Oven (105˚C)	Intact cores ($\mathrm{V} = 348\ \mathrm{cm}^3$)	Structural, normal[a]	-	
Lehrkamp (1987)	-	-	($\mathrm{V} = 100–214\ \mathrm{cm}^3$)	-	-	
Berglund (1989)	*m*	Vacuum-desiccator (55˚C)	-	-	-	
Pyatt and John (1989)	w-f	Oven (105˚C)	Intact cuboids ($\mathrm{V} = 250\ \mathrm{cm}^3$)	Normal, residual[a]; near-, sub-, supernormal[b]	Linear-cube root	2
Szatylowicz et al. (1996)	w-sr	Oven (105˚C)	Clods ($\mathrm{V} = 34–107\ \mathrm{cm}^3$)	-	Three-straight-lines	6
Oleszczuk et al. (2000)	w-sr	Evaporation and oven (105˚C)	Intact cores ($\mathrm{V} = 34–107\ \mathrm{cm}^3$)	Sub-, supernormal[b]	Three-straight-lines	3
Schwärzel et al. (2002)	m	Tension and pressure	Intact cores ($\mathrm{V} = 100\ \mathrm{cm}^3$)	-	-	
Oleszczuk et al. (2003)	m	Evaporation	Intact cores ($\mathrm{V} = 98–487\ \mathrm{cm}^3$)	Structural, normal[b]; sub-, supernormal[b]	Three-straight-lines	4
Hendriks (2004)	w-sr	Evaporation and oven	Intact cuboids ($\mathrm{V} = 27–125\ \mathrm{cm}^3$)	Near-, sub-, supernormal[a]	Exponential	7
Michel et al. (2004)	o	Evaporation	Disturbed cores	-	-	
Kennedy and Price (2005)	w-sr	Oven (70˚C)	Intact cuboids	Normal, residual, zero[a]	Exponential	
Peng and Horn (2007)	m+o	Oven (40, 70, and 105˚C)	Intact cores ($\mathrm{V} = 479\ \mathrm{cm}^3$)	Structural, normal[a]	Sigmoidal	2
Oleszczuk and Brandyk (2008)	w-sr	Evaporation and oven (105˚C)	Intact clods ($\mathrm{V} = 30–60\ \mathrm{cm}^3$)	-	-	3
Kechavarzi et al. (2010)	m	Tension and pressure	Intact cores ($\mathrm{V} = 39\ \mathrm{cm}^3$)	Structural, normal, residual[a]	Sigmoidal	6
Gebhardt et al. (2010, 2012)	m+o	Tension and pressure	Intact cores ($\mathrm{V} = 470\ \mathrm{cm}^3$)	Structural, normal, residual[a]	-	3
Dissanayaka et al. (2012)	m	Tension and oven (30, 105˚C)	Intact cores ($\mathrm{V} = 100\ \mathrm{cm}^3$)	-	-	
Horn et al. (2014)	m	Tension, pressure, and oven (105˚C)	Intact cores ($\mathrm{V} = 470\ \mathrm{cm}^3$)	Structural, normal[a]	-	2

(Continues)

TABLE 1 (Continued)

Study	Method V	Method for desiccation	Sample type/size	Shrinkage phases	Model	n
Hamamoto et al. (2016)	m	Tension, pressure, and oven (105°C)	Intact cores ($V = 100$ cm^3)	-	-	
Perdana et al. (2018)	-	-	*Disturbed cores*	-	-	
John et al. (2021)	m	Tension and pressure	Disturbed cores	-	-	

Note: italic = presumably, V = volume; abbreviations for methods for volume determination (Method V): (1) displacement media: w = water, hg = mercury, gb = glass beads, s = sand; (2) coatings: p = paraffin, sr = Saran resin (or similar vapor permeable material), f = plastic film; and (3) geometric measurements: m = mechanical, o = optical (including 3D scanning), m+o = combination of mechanical and optical measurement, *n*: Number of horizons/layers used in the meta-analysis.

[a]Explicitly described in the respective study.

[b]Derived from plotted data (depending on metrics).

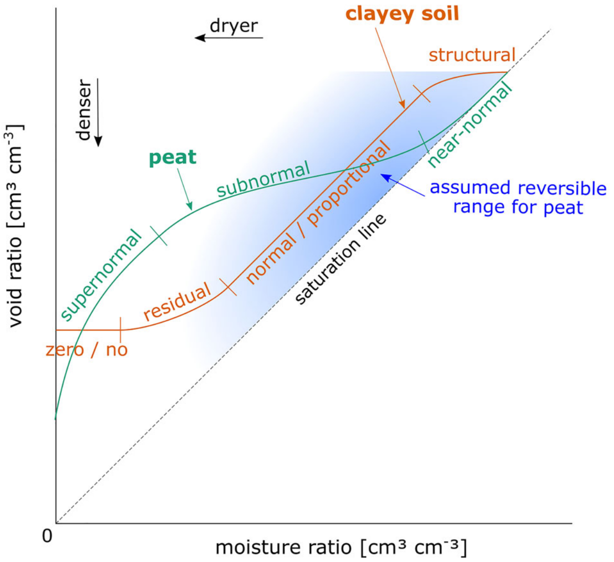

FIGURE 1 Exemplary soil shrinkage characteristic (SSC) of (a) clayey (Beck-Broichsitter et al., 2020; Peng & Horn, 2007) and (b) peat soil (Hendriks, 2004; Pyatt & John, 1989). The axes are not true to scale.

are not shown here, but listed in Table S2 of the supplemental material.

In the following sections of Part I, all studies are mentioned, including those which were excluded from the meta-analysis (Part II).

2.1 | Shrinkage phases and soil shrinkage characteristic

The relationship between soil volume and soil moisture or pressure head is termed "soil shrinkage characteristic (SSC)." Shrinkage can be separated into different shrinkage phases (also called "zones" or "ranges"). The number and shape of the observed phases vary among different studies in dependence on the structural (e.g., botanical constituents and their degree of decomposition) and mineralogical soil properties (e.g., clay content and composition of clay minerals [Dinka & Lascano, 2012]), the measurement approach, and the used metrics (Szatylowicz et al., 1996).

Figure 1 shows two exemplary SSCs for clayey soil and peat. There are four shrinkage phases which can often be found for clayey soils. From the wet to the dry end of the curve, these are as follows:

(1) **Structural shrinkage:** The soil volume reduction is smaller than the loss of water (Stirk, 1954). Large stable pores keep their volume during dewatering (Yule & Ritchie, 1980). The existence and characteristic of these large pores depend on the structural properties of the soil matrix (Mitchell, 1991).

(2) **Normal or Proportional shrinkage:** The soil volume reduction equals the loss of water (Haines, 1923). Soil volume decreases due to the contraction of dewatering pores and air does not replace lost water (Yule & Ritchie, 1980). This part of the shrinkage curve is parallel to the 1:1 line of void ratio and moisture ratio, also called “saturation line” (McGarry & Malafant, 1987).

(3) **Residual shrinkage:** The soil volume reduction is smaller than the loss of water and air is entering the dewatered pores (Haines, 1923). In difference to the structural shrinkage, where the remaining (larger) pore size depends on structural properties, here the remaining (smaller) pore size is limited by the particle size of the soil. During dewatering, the particles come to close contact and limit volume reduction (Stirk, 1954).

(4) **Zero or No shrinkage:** The soil volume reaches its minimum and is not decreasing. The remaining minimum pore size depends on texture (Stirk, 1954). Removed water is completely replaced by air.

The shrinkage behavior of peat strongly differs from that of clayey soils. The exemplary shape shown in Figure 1 was described by several studies for different types of peat (e.g., Hendriks, 1997; Hendriks, 2004; Oleszczuk et al., 2000, 2003; Pyatt & John, 1989; Szatylowicz et al., 1996). Due to the strong divergence from clay SSCs, Hendriks (2004) adapted the naming-concept for clay soils and distinguished the three following shrinkage phases for peat:

(1) **Near-normal shrinkage:** The soil volume reduction nearly equals the loss of water.

(2) **Subnormal shrinkage:** The soil volume reduction is smaller than the loss of water, while air enters large pores and small pores keep water filled.

(3) **Supernormal shrinkage:** The soil volume reduction is greater than the loss of water while air enters small pores and large pores collapse.

A major challenge when comparing SSCs and shrinkage phases from different studies is the use of different volume and moisture metrics (Table 2) as the shape of the SSC and the shrinkage phases depend on the choice of metrics (Szatylowicz et al., 1996). In most cases, we could not convert these metrics into each other as information on soil properties were lacking (e.g., volume of solids). Generally, since the early 1990s, the dimensionless metrics void ratio (e) and moisture ratio (ϑ) have been prevailing. In older studies, however, different combinations of the other metrics are shown in Table 2 and also more basic metrics, for example, water volume (cm^3), water tension (kPa) (or pF [−]), soil volume (cm^3), or volume reduction (%), had been used. Thus, it is possible that an SSC of an organic soil in a void ratio–moisture ratio plot that follows the near-normal–subnormal–supernormal scheme can look similar to the "classical" (structural–normal–residual–zero) scheme if it is plotted with recent bulk density ($\rho_{b,r}$) versus ϑ instead.

Keeping the problem of different metrics in mind, we discuss the following reasons behind different shapes of the SSC and shrinkage phases identified by different studies (Table 1). In contrast to the naming-concept introduced by Hendriks (2004) (Figure 1), Pyatt and John (1989) suggested to distinguish shrinkage of peat into two sections, without and with cracking. The first section, without cracking, corresponds to the normal or near-normal shrinkage phase and the second section, with cracking, unites subnormal and supernormal shrinkage. According to these authors, the development of shrinkage phases of organic soils depends on the degree of decomposition. Well-decomposed (sapric) pseudo-fibrous and amorphous peat did not show structural, but normal or near-normal shrinkage throughout a very wide range of water content and even little residual shrinkage was suggested. However, fibrous peat showed more pronounced subnormal and supernormal shrinkage during crack formation. These results and data published by Hendriks (2004), Peng and Horn (2007), and Gebhardt et al. (2010, 2012) indicate that the SSC of organic and organic rich (organo-mineral) soils becoming similar to the typical clay SSC with increasing degree of decomposition, decreasing organic matter content, and increasing mineral content. Furthermore, data published by Ilnicki (1967) and Oleszczuk and Brandyk (2008) indicate that the botanical composition, especially the presence of moss remains, influence the shape of the SSC. It has to be mentioned, that these two latter studies did not use void ratio and moisture ratio which makes a comparison more difficult.

Kechavarzi et al. (2010) investigated the shrinkage behavior of six organic soils and found predominantly sigmoidal SSCs, that is, the typical shape of clay SSCs (Figure 1). An issue of this study is a lack of measurements in the lower half of the moisture range, which can lead to questionable fittings of the sigmoidal model.

Peng and Horn (2013) analyzed shrinkage data of different studies and identified six types of SSCs (A–F) for mineral and organic soils. Mineral soils represented the majority in their study. Most organic soils belong to the type C category which is characterized by two classical shrinkage phases, structural and normal/proportional shrinkage. As most of the organic soils used in their study had rather low contents of SOC (<30%), this confirms the hypothesis that the shape of the SSC becoming more similar to the typical SSC for mineral soils with increasing mineral content (with decreasing SOC). As the data for organic soils with SOC contents higher than 40% originated from the studies of Kechavarzi et al. (2010) and Kennedy and Price (2005) whose SSCs lacked of measurements at the dry end of the curve, this can lead to misinterpretation, as this part is crucial to decide between different SSCs or adequate shrinkage models.

TABLE 2 Volume and moisture metrics.

Volume		Moisture	
	$e = \frac{V_{\text{voids}}}{V_{\text{solids}}} = \frac{V_{\text{soil}} - V_{\text{solids}}}{V_{\text{solids}}}$		$\vartheta = \frac{V_{\text{water}}}{V_{\text{solids}}} = \frac{m_{\text{water}}}{\rho_{\text{water}} \cdot V_{\text{solids}}}$
Void ratio	$e = \frac{V_{\text{soil}}}{V_{\text{solids}}} - 1 \left[\frac{cm^3}{cm^3}\right]$	Moisture ratio	$\vartheta = \frac{m_{soil} - m_{solids}}{\rho_{water} \cdot V_{solids}} \left[\frac{cm^3}{cm^3}\right]$
Specific volume	$\upsilon = \frac{V_{\text{soil}}}{m_{\text{solids}}} \left[\frac{cm^3}{g}\right]$	Gravimetric water content	$\theta_g = \frac{m_{\text{water}}}{m_{\text{solids}}} \left[\frac{g}{g}\right] \ or\ [\%]$
Recent bulk density	$\rho_{b,r} = \frac{m_{\text{soil}}}{V_{\text{soil}}} \left[\frac{g}{cm^3}\right]$	Volumetric water content	$\theta_\upsilon = \frac{V_{\text{water}}}{V_{\text{soil}}} \left[\frac{cm^3}{cm^3}\right] \ or\ [\%]$

Abbreviations: ρ, density; m, mass; V, volume.

A major challenge when describing shrinkage–swelling behavior of both mineral and organic soils is hysteresis (Ilnicki, 1967; Michel et al., 2004; Peng & Horn, 2007). In contrast to organic soils, clayey soils can regain a huge share, about 74%–90% (Peng & Horn, 2007), of the lost soil volume during rewetting after oven drying. Organic soils regain much less volume, only 22%–23% (Peng & Horn, 2007) or 5%–30% (Ilnicki, 1967). According to Illner (1977, 1982) and Oleszczuk and Brandyk (2008), strongly decomposed earthified organic top soils can regain their volume (almost) completely after air drying and rewetting whereas less decomposed peat soils, especially if they originate from deeper layers, cannot.

2.2 | Measurement approaches

Shrinkage of soils is measured in the laboratory because it is not possible to experimentally separate it from other processes in the field. Shrinkage experiments are either used to determine the whole SSC, $S_{\max}$ (shrinkage from saturation to oven drying), or both. Measurements of shrinkage depend on the accurate determination of soil volume and can be broadly separated into "displacement," "replenishment," and "geometry" based approaches. All methods can be applied to both organic and mineral soils. Thus, we do not distinguish between methods for mineral or organic soils here. Advantages and disadvantages of the methods are listed in Table 3.

For the **displacement** based approach, the sample is immersed into a container filled with water (Luikov, 1935), kerosene (Stirk, 1954), toluene (Drnevich et al., 1989), or mercury (Haines, 1923). Afterwards, the volume is determined by weighing or measuring the displaced volume (e.g., graduated-cylinder or burette apparatus by Johnston, 1945). This allows the use of intact soil clods (Brasher et al., 1966; Bronswijk et al., 1997). To avoid penetration of the liquid into the sample, "non-penetrating" liquids like mercury can be used or the samples have to be coated with melted paraffin wax (Luikov, 1935), Saran resin (polyvinylidene chloride, Dow Chemical Company) (Brasher et al., 1966), plastic film (Pyatt & John, 1989), or material with similar properties. Tunny (1970) showed that Saran resin restrains shrinkage and swelling of coated clods. Nevertheless, this method was used in five of the identified studies and the results of these studies do not indicate a systematic reduction of measured shrinkage. The paraffin wax coating method is suggested to be the most accurate and easiest way of volume determination, but due to the potential loss of material through the removal of the coating for further drying or wetting, it is recommended to use individual samples for each measured pressure head or soil moisture (Cornelis et al., 2006). Tariq and Durnford (1993b) introduced a balloon apparatus, using the known approach of liquid displacement, but eliminating the mentioned problem of coating. The soil sample is filled into a rubber balloon and air passes through the balloon to dry the sample. To determinate the sample volume, the space around the sample can be evacuated and the balloon can be lowered into a beaker filled with water.

Since organic soil samples are characterized by low bulk densities (below 1 g cm^{-3}), they float on water and it is necessary to attach additional weights which complicates the measurement procedure and data processing (Bronswijk et al., 1997).

For the **replenishment** approach, emerged voids between the sample and the sampling ring (or other containers of

TABLE 3 Comparison of volume measurement methods.

Approach	Variant	Advantages	Disadvantages
Displacement	Without coating	Direct measurement of volume of irregularly shaped samples	Use of non-penetrating liquid (e.g., mercury) which may be toxic
	With Saran resin coating	Water can be used as liquid, coating is vapor permeable	Coating may influence shrinkage
	With other coating	Water can be used as liquid	Coating is not vapor permeable and must be removed or separate samples have to be used for each moisture level
	Balloon apparatus	Water can be used as liquid, sample can desiccate in balloon, volume of the same sample can be determined for different moisture levels	Depending on balloon material and applied suction it may be hard to apply to very soft undisturbed samples (e.g., fibric moss peat)
Replenishment		Direct measurement of the volume of irregularly shaped samples	Accuracy depends on particle size of filling material, separate samples have to be used for each moisture level
Geometry	Mechanical	Easy, cheap, and fast to apply, volume of the same sample can be determined for different moisture levels	Accuracy depends on the shape of the sample and number of measurement points, low accuracy for irregular shapes
	Mechanical and optical	May be more accurate than solely mechanical measurements, volume of the same sample can be determined for different moisture levels	Accuracy gain and representativity depends on measurement setup
	Optical (3D scanning)	Accurate measurement of volume of irregularly shaped samples, volume of the same sample can be determined for different moisture levels	Measurements are more time-consuming (depending on scanner and computing power), may be hard to apply to crumbling samples (e.g., amorphous top soils) due to frequent moving and turning

known volume) are filled up with a granular material of a known ρ_b, for example, sand, glass, or metal beads (Päivänen, 1982; van Dijk & Boekel, 1965; Vidal & Schuch, 1966). Analogue to the paraffin coating method, continuous volume measurements cannot be performed with this method, as it is not possible to regain the added material completely after measurement (Päivänen, 1982). Probably due to this limitation, replenishment was used only by three studies.

With **geometry** based approaches, the physical dimensions of the sample are measured mechanically by ruler (Tempany, 1917), calipers (Ilnicki, 1967), a dial gauge (Berndt & Coughlan, 1977), a micrometer (Oleszczuk et al., 2003), a circumference meter (Schindler et al., 2015), or optically by laser (Garnier et al., 1997). Geometry based methods are the most common ones and were used by 17 studies. For determining crack formation, image analysis can be used and combined with other mentioned methods to calculate soil volume (Peng & Horn, 2007). As an advancement of two-dimensional image analysis, 3D scanning of the sample top allows the direct measurement of the sample height and diameter at the top (Seyfarth et al., 2012). The major challenge when using geometric based methods is to achieve a sufficient accuracy and representativity of the measured dimensions, especially in case of irregular shrinking samples. This is given with full 3D scanning of the sample, either by a 3D structured light scanner (Sander & Gerke, 2007), a 3D laser scanner (Rossi et al., 2008) or a series of digital uniformly illuminated photographs (Stewart et al., 2012). These latter methods are grouped as optical ones.

There have been attempts to determine shrinkage behavior from field measurements of ρ_b and soil water content at different points in time (Hewelke et al., 2016), surface motion (Mitchell, 1991; Morton & Heinemeyer, 2019; Schothorst, 1977; Woodruff, 1937), or measurement of the crack size (Bronswijk, 1991; Zein El Abedine & Robinson, 1971). But as shrinkage at the field scale is overlain by other processes and influenced by vegetation (especially roots), results are hardly comparable with those from measurements performed in laboratory. Furthermore, different measurement approaches were developed with different scopes (e.g., subsidence, water infiltration, or root anchoring) and consider different dimensions of shrinkage (e.g., one-dimensional: elevation change or crack width, two-dimensional: crack width and depth, and three-dimensional: bulk density).

2.3 | Shrinkage models

Various functions describing the SSC of different clayey and organic soils have been published over the last decades. The majority of the existing functions was developed for clayey soils. Some commonly used models can be found in the supplemental material (Figure S1). Commonly, SSCs are described by continuous or composite functions. Linear, cubic (Luikov, 1935), exponential (Hendriks, 2004; Kim et al., 1992), polynomial (Giráldez et al., 1983), and sigmoidal/logistic (Groenevelt & Bolt, 1972; McGarry & Malafant, 1987; Peng & Horn, 2005, 2007) functions were used for a continuous description of the SSC. For composite functions, specific parts of the SSC were separated into single shrinkage phases (Olsen & Haugen, 1998) or by the beginning of crack formation (Pyatt & John, 1989) or air entry (McGarry & Malafant, 1987). The number of sections differed (in most cases two or three) depending on soil properties and study. Again, the different sections were described by linear (McGarry & Malafant, 1987; Oleszczuk et al., 2000), polynomial (Chertkov, 2003; Tariq & Durnford, 1993a), exponential (Braudeau, 1988), hyperbolic (Olsen & Haugen, 1998), or root (Pyatt & John, 1989) functions.

Using a different approach, Stewart et al. (2016) distinguished between three types of porosity (aggregate-, crack- and subsidence-porosity) and developed a continuous shrinkage model describing the volume change of these porosities due to the change of moisture conditions.

There were only a few functions specifically developed for organic soils, such as the linear and cubic functions of Luikov (1935), the composite functions (two sections) of Pyatt and John (1989) (modified by Camporese et al., 2006), or Hendriks' (2004) exponential function (Figure 2). The mathematical formulation of the models shown in Figure 2 are listed in Table S3.

Most mathematical models, especially composite ones, are very flexible and can take different shapes, depending on their parametrization. Hence, some of the models developed for clayey soils can also be parameterized for organic soils. A good example for this is the three-straight-lines model which was applied by McGarry and Malafant (1987) to clayey soils and by Oleszczuk et al. (2000, 2003) to organic soils. The flexibility is underlined by very high model efficiencies, for example, R^2 of 0.91–0.97 (Oleszczuk et al., 2000), 0.96–0.99 (Oleszczuk et al., 2003), and 0.998 (Peng & Horn, 2007). However, flexibility and a large number of parameters hampers the transferability, especially as shrinkage models have to be validated by applying them to independent samples. Furthermore, to our best knowledge, no attempt has been made to relate the parameters of shrinkage models to soil properties such as degree of decomposition, peat substrate, or ρ_b.

3 | PART II: META-ANALYSIS OF LITERATURE AND OWN DATA ON MAXIMUM SHRINKAGE

3.1 | Material and Methods

In this section, we analyzed data from studies which fulfilled all criteria defined above (part I) and marked in Table 1. Studies which had to be excluded (Table S1) are not considered here. A lack of comparable data precluded an evaluation of SSCs as only a few studies reported full SSCs, and, moreover, these studies used different shrinkage and/or moisture metrics and do not give full information on peat properties. As $S_{\max}$ (Equation 1) was given in most studies or could be derived from the published data, we had to restrict our analysis to this parameter. Here, $V_{\text{saturated}}$ is the sample volume at saturation and V_{ovendry} is the volume after oven-drying (at least 80°C).

$$S_{\max} = \frac{V_{\text{saturated}} - V_{\text{ovendry}}}{V_{\text{saturated}}} \times 100\% \tag{1}$$

3.1.1 | Classifications and data aggregation

The organic soils of all considered studies were classified into "fibric," "hemic," and "sapric" following the U.S. Soil Taxonomy (Soil Survey Staff, 1999). When studies did not provide this information, classification was performed using reported values of ρ_b and θ_g at saturation or degree of decomposition according to von Post's (1922) classification scheme (H1–H10) as shown in Table S4. As in Dettmann et al. (2019), the conversion from the von Post scheme to the fibric-hemic-sapric scheme deviates slightly from guidelines for soil description (Jahn et al., 2006) to achieve a more balanced sample distribution. Organo-mineral soils do not have a degree of decomposition. Furthermore, one of the two peat types "bog peat" or "fen peat" were assigned, depending on the origin of the soil sample and its botanical composition. Samples from transition mires were treated as fen peat. No peat type was explicitly assigned to organo-mineral samples, but site or profile description lead us to the conclusion that all organo-mineral samples in this study were derived from fen peat.

Peat substrates were aggregated into moss peat, peat from graminoid species, wood peat, mixed substrates (mosses and graminoids), amorphous peat, and organo-mineral substrates (Table 4). Although we are aware that the different peat-forming graminoid species results from widely different hydrological and ecological conditions, the data set was too small to distinguish, for example between *Phragmites* and *Carex* peat.

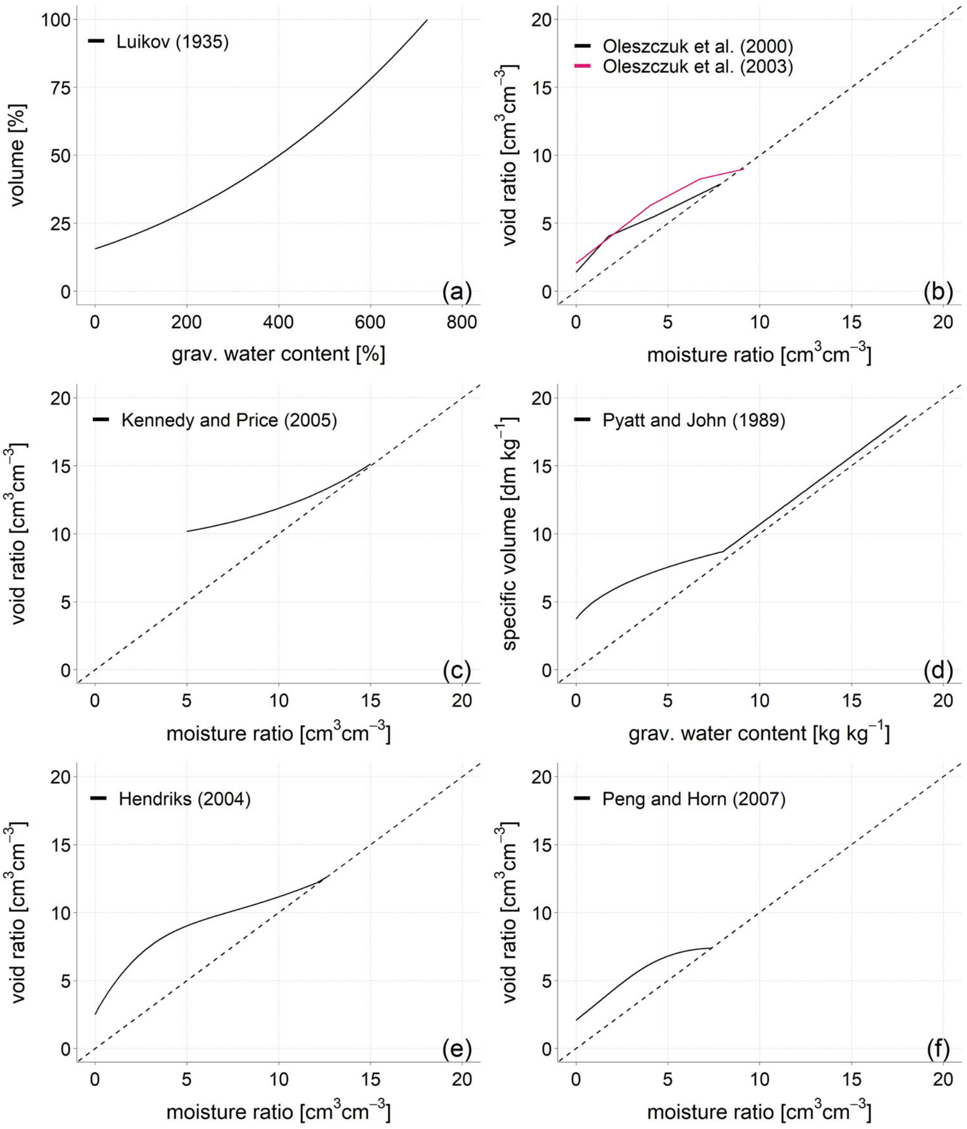

FIGURE 2 Exemplary courses of different shrinkage models used for peat and other organic soils. Parameters were taken/estimated from the respective studies. (a) cubic model (Luikov, 1935), (b) three-straight-lines model for two different data sets (Oleszczuk et al., 2000, 2003), (c) exponential model (Kennedy & Price, 2005), (d) linear-cube root model (Pyatt & John, 1989), (e) exponential model (Hendriks, 2004), (f) sigmoidal model (Peng & Horn, 2007) (organo-mineral soil). For mathematical formulations see Table S3. grav. water content, gravimetric water content.

TABLE 4 Classification of peat substrates in this study.

Class	Abbreviation	Substrate
Moss	moss	Clearly dominated by *Sphagnum* species or brown mosses
Graminoid	gramin.	*Phragmites, Scheuchzeria, Carex, Eriophorum, Cladium*, and other graminoids
Wood	wood	Any kind of wood, such as birch, alder, pine (>35% wood constituents)
Moss and graminoid	m+g	Mixed substrates (e.g., *Sphagnum* with *Eriophorum*)
Amorphous	amorph	Plant remains are not determinable, but with SOC ≥15% (amorphous peat)
Organo-mineral	o-m	soils with SOC between 7.5% and 15%

Abbreviation: SOC, soil organic carbon content.

Good images of the composition and structure of different peat types were published by several authors, for example, Boelter (1969), Schulz et al. (2019), and McCarter et al. (2020).

3.1.2 | Conversion between ash content, soil organic matter, soil organic carbon content, and dry bulk density

SOC content and bulk density (ρ_b referred to fresh/saturated volume) were not provided by all studies. However, for a systematic comparison and due to their possible influence on shrinkage, we estimated them from other given soil properties, if necessary. In many cases, either ash content (AC) or loss on ignition (LOI = 100 − AC [%]) was given instead of SOC. SOM content (equal to LOI) was then converted into SOC by the factor 0.5 (Ad-hoc-AG Boden, 2005). In some cases, ρ_b needed to be estimated from SOC or vice versa by $\rho_b = -0.35 \times \ln(\mathrm{SOC}) + 1.51$ (Wittnebel et al., 2021; "all samples," root-mean-square error [RMSE] = 0.11 g cm^{-3}).

3.1.3 | Laboratory study

Own volume measurements to determine $S_{\max}$ were carried out at 579 oven-dried (80˚C or 105˚C) organic soil samples from 136 soil horizons from all over Germany and several other European countries. Samples were taken vertically from specific horizons with sharp edged steel cylinders with a diameter of 7.2 cm and a height of 6.0 cm. The cylinders were hammered carefully into the soil and then the whole sample was excavated and checked for any signs of compression, damage, or edge effects. The protruding material was then carefully cut using scissors and serrated knives. The number of replicates per site and horizons varied between one and seven (in most cases three to six) due to the fragility of the samples, especially of amorphous earthified top soils. The soil profiles were fully described and classified regarding peat substrate (Table 4) and degree of decomposition according to von Post (1922). Bulk densities (related to saturated volume) were determined by dividing the sample mass after drying the samples at 80˚C (Dettmann et al., 2019) or 105˚C (Dettmann et al., 2022) by the volume of the saturated samples ($V_{\mathrm{saturated}}$ = 244.29 cm^3). Total carbon (TC) and total inorganic carbon (TIC) content of carbonate containing samples were measured at separate samples of the same soil horizons by dry combustion (RC 612/TRUMEC, LECO Corporation), and SOC was then calculated as SOC = TC − TIC.

The volumes of the oven-dried samples (V_{ovendry}) were determined by scanning them with a 3D structured light scanner (RangeVision Spectrum). The volume of the 3D models was calculated by the open source 3D graphic suite Blender (Blender Foundation). In contrast to former publications by Sander and Gerke (2007), Rossi et al. (2008), and Dinka and Lascano (2012), this process only took about 10 min per sample. Repeated scanning (four times) of a single sample showed a very low uncertainty for the determined volume with a standard deviation of 0.3 cm^3 (0.2%).

Two data points (soil horizons) were removed from the data analysis, due to exceptional high ρ_b values (substrate specific).

3.1.4 | Data analysis

Statistical analysis was performed with R (R Core Team, 2022). Generally, mean values of single horizons were used. To investigate the effects of the degree of decomposition and peat type (bog peat or fen peat) and peat substrate composition on $S_{\max}$, two linear mixed effects models (lme from the R package nlme by Pinheiro et al., 2022) were fitted. Linear mixed effects models were used due to the unbalanced group sizes, heteroscedasticity, and the potential effect of different volume measurement methods. The two models used (i) the combination of degree of decomposition and peat type and (ii) the substrate composition as fixed effects. The heteroscedasticity was accounted for by applying a variance structure which allows individual variances for each group (varIdent). Different volume determination methods were considered as random effects. The distributions of the residuals of the two fitted models were checked visually. A normal distribution for substrates and a near-normal distribution for degree of decomposition were found which indicated a suitable model selection. To identify significant differences between the mean $S_{\max}$ values of the groups, pairwise testing with a significance level $\alpha = 0.05$ was performed by applying the emmeans function (Russell, 2022) to the fitted models.

To investigate the relationship between $S_{\max}$ and (1) SOC and (2) ρ_b second-order polynomial models (Equation 2) were fitted to bootstrapped data sets (n = 10,000) separated into (1) bog and fen peat soil and (2) substrate (Table 4) using the function lm (R Core Team, 2022). From these fitted models the parameters representing the median and 2.5% and 97.5% quantiles were determined. Second-order polynomials were chosen due to the results of the linear mixed effects models which indicated a curved relationship. Furthermore, second-order polynomials gave slightly better fits (smaller R^2, coefficient of determination) compared to first-order polynomials.

$$S_{\max} = a \cdot x^2 + b \cdot x + c \tag{2}$$

In total, shrinkage data from 408 horizons or layers were analyzed. It has to be mentioned that the data set was dominated by the study of Ilnicki (1967) (n = 235) and our own

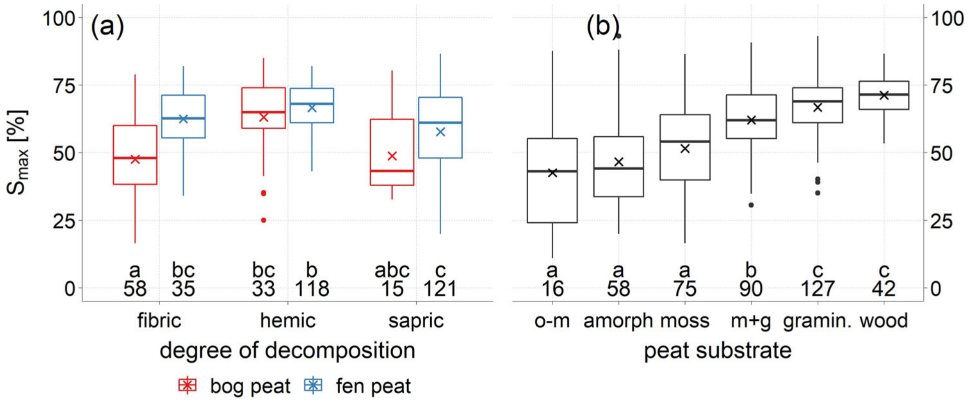

FIGURE 3 Maximum shrinkage (S_{max}) in dependence on (a) degree of decomposition and (b) peat substrate. Crosses show the mean values. Same letters (a–c) indicate nonsignificant differences ($\alpha = 0.05$). Numbers indicate sample size for each group. gramin., graminoid; m+g, moss and graminoid; o-m, organo-mineral.

measurement data (n = 134). Therefore, we tested whether the S_{max} values for all substrate classes differed significantly between the data origins by fitting a linear model with the generalized least squares method (gls from R package nlme by Pinheiro et al., 2022) and pairwise testing (emmeans by Russell, 2022).

3.2 | Results and discussion

3.2.1 | Influence of degree of decomposition and peat substrate on maximum shrinkage

Figure 3 shows the differences in S_{max} for organic soils with (a) different degrees of decomposition stratified by peat type and (b) peat substrates. Due to the data properties (unbalanced sample size and heterogeneous variances), the visual impression of the boxplots can deviate slightly from calculated significances.

The degree of decomposition had an influence on S_{max} values and on whether S_{max} significantly differed by peat type (Figure 3a). Organo-mineral soils are not included here as no degree of decomposition can be assigned to them. On average, fen peats had higher S_{max} values for all degrees of decomposition, but the effect of the peat type was only significant for fibric soils with median values of S_{max} of 48% for bog and 63% for fen peats. Differences between bog and fen peats of the hemic and sapric classes were not significant. Further, in contrast to bog peat, there were no difference between the different degrees of decomposition for fen peat. A reason for the lower S_{max} of fibric bog peats compared to fibric fen peat and hemic bog and fen peat could be a more rigid stabilizing structure of well-preserved *Sphagnum* remains that result in larger pores during drying. On the other hand, the shrinkage of sapric soil was limited by its generally higher ρ_b, that is, smaller shrinkable pore-space due to higher content of fine material and small pores without (or with less) stabilizing plant remains. The pore structure of hemic peat is intermediate, stabilizing strong fibers and other plant remains are more decomposed and weakened but the content of fine material is not as high as content of sapric soils. Rezanezhad et al. (2016) and McCarter et al. (2020) found that pore sizes decrease due to decomposition, shrinkage, and compression which confirms the interpretation of decreasing fiber stability and shrinkable pore-space due to decomposition.

Figure 3b shows increasing shrinkage in the order organo-mineral soil < amorphous peat < moss peat < mixed (moss and graminoid) peat < graminoid peat < wood peat. Although some of these classes were rather similar in their S_{max} values, three significantly different groups of the substrate could be differentiated. Organo-mineral soil, amorphous peat, and moss peat showed significantly lower S_{max} values than the other substrate classes but did not differ significantly from each other. The values of S_{max} of mixed peats (moss and graminoid) were significantly higher than those of this first group of classes, but lower than those of graminoid and wood peats, which seems logical due to shrinkage characteristics of individual components of the mixture. Graminoid and wood peats showed significantly higher S_{max} values than all other classes, but did not differ significantly from each other.

By definition, amorphous organic soils are strongly decomposed, have no visible plant remains and may already contain mineral substrates. Organo-mineral soils show even higher contents of mineral constituents. Both lead to high values of ρ_b. Thus, the relatively low S_{max} values were not surprising. Furthermore, most amorphous (earthified) soils have been subjected to numerous intense shrink-swell cycles before, which reduce the potential of further shrinkage (Illner, 1982; Oleszczuk & Brandyk, 2008).

Moss peats were predominantly (65%) classified as fibric which led to relatively low ρ_b and S_{max} values. As the majority of the moss peat samples originate from bog peat, these relatively low values are in line with the comparison between bog and fen peat shown in Figure 3a. Mixed (moss and graminoid) and graminoid peats were predominantly (62% and 47%, respectively) characterized as hemic, whereas sapric was the dominant class (60%) for wood peats. This suggests a higher structural stability of soils which contain mosses which reduces shrinkage compared to more decomposed peats without a rigid moss structure. Graminoid and wood peats predominantly showed median ρ_b values of 0.17 and 0.20 g cm^{-3}, respectively, which were high compared to 0.10 g cm^{-3} of moss peats and 0.12 g cm^{-3} of mixed peats but seemed to be sufficiently low to reach median $S_{\max}$ values of approximately 70%. The high $S_{\max}$ values for wood peat are somewhat surprising, as one might expect wood remains stabilize the pore structure. Furthermore, the matrix of wood peat is amorphous — which usually tends to infer lower $S_{\max}$ — and ρ_b values were comparatively high. Nonetheless, data on wood peat came from three different sources (own data; Ilnicki, 1967; Oleszczuk et al., 2003). Furthermore, Dettmann et al. (2014) found higher shrinkage of amorphous peat from an alder forest than from other peat with higher SOC content which all suggests a systematic effect.

Ilnicki (1967) and Päivänen (1982) found that $S_{\max}$ depends on peat substrate, too. According to Ilnicki (1967) sedge peats (here included into the graminoid class) and wood peats showed the highest values of $S_{\max}$ and he also found that mosses reduced $S_{\max}$ values. As his data were incorporated into this study these similar results were not surprising. But even when only our own measurements are considered, the described patterns stay the same, with slightly deviating significances (Seidel et al., 2023). Päivänen (1982) found $S_{\max}$ to be largest for moss (*Sphagnum*) peats with mean $S_{\max}$ = 52.5%, which fits well to the values shown in Figure 3b. However, he found substantially lower $S_{\max}$ values for graminoid (*Carex*) and wood peats of 45.8% and 45.1%, respectively.

The large spread of the data might in parts be caused by the differing terminologies (also due to the vastly different age of the studies) and varying experience with peat soil of the authors of the studies. We tried our best to correctly interpret the description of the peat, but we cannot exclude misinterpretation in some cases.

3.2.2 | Influence of soil organic carbon and bulk density on maximum shrinkage

In Figure 4, the relationships between $S_{\max}$ and (a) SOC and (b) ρ_b are shown. The corresponding parameters of the fitted second-order polynomial equations (Equation 2) for bog and fen peat soils are listed in Table S5. Furthermore, the same equation (Equation 2) was fitted to data sets separated by substrates (Figures 5 and 6, Table S6). All relationships are completely empiric and the fitted parameters are only valid within the range covered by measurement data.

Generally, a large spread of $S_{\max}$ and SOC values but also an increase of $S_{\max}$ with SOC, especially for fen peat soil is visible (Figure 4a). The large spread of $S_{\max}$ values led to very low coefficients of determination ($R^2{}_{\mathrm{SOC}}$) of 0.04 and 0.14 for bog and fen peats, respectively, and relatively high RMSE$_{\mathrm{SOC}}$ values of 15% and 13%. Thus, SOC seemed to be a weak estimator for $S_{\max}$ especially for bog peat soils. One reason is that bog peat has naturally a lower range of SOC (no addition of mineral material by, e.g., flooding), another one is that SOC had to be estimated in many cases from AC (n = 244) or in few cases from bulk density ($n = 2$) using empirical equations. This led to the visible cluster between 40% and 50% SOC, especially for moss and mixed peats (Figure 5c,d). Further, while bog peat is predominantly composed of *Sphagnum*, fen peat is much more heterogenous. As discussed above, especially sapric fen peat showed a large spread in $S_{\max}$ values, accordingly.

When analyzing different substrates separately, we found that $R^2{}_{\mathrm{SOC}}$ was much higher for organo-mineral soils (a) and wood peat (f) (0.26 and 0.38, respectively) compared to the other substrates which showed very low $R^2{}_{\mathrm{SOC}}$ values below 0.1, that is, (nearly no) relationship between SOC and $S_{\max}$ (Figure 5). As expected, organo-mineral soils had decreasing $S_{\max}$ values with decreasing SOC, but also a very wide range of $S_{\max}$ from 11% to 88%. Besides differences in the history of land-use and hydrological conditions, this large range can be caused by the composition of the mineral constituents, for example, sand or clay. As clay itself is a shrinking material, whereas sand is not, this had a strong influence on the shrinkage of organo-mineral soils. Unfortunately, data on the mineral constituents of the samples is largely lacking.

$S_{\max}$ of wood peats first increased with increasing SOC up to around 40% and decreased for higher SOC contents. As this latter decrease was derived from only few points the shape of the curve should not be over-interpreted. The increase of $S_{\max}$ with SOC could be caused by decreasing ρ_b with increasing SOC (Wittnebel et al., 2021) and accordingly increasing porosity (Landva & La Rochelle, 1983).

The large scatter and poor fitting of the other substrate classes can at least in parts be ascribed to the substrate classification and the differences within the substrate classes, for example, regarding degree of decomposition, plant composition, and shrinkage history. The "amorphous" class (b) consists of strongly decomposed earthified top soils of drained agriculturally used peatlands and lower-lying organic soils without determinable plant remains but without a pronounced shrink-swell history. Additionally, these substrate class is characterized by considerable amounts of mineral constituents, which, in most cases, predominantly consist of sand or clay strongly differing in shrinkage behavior. Thus, clayey peat is expected to shrink much stronger than sandy peat

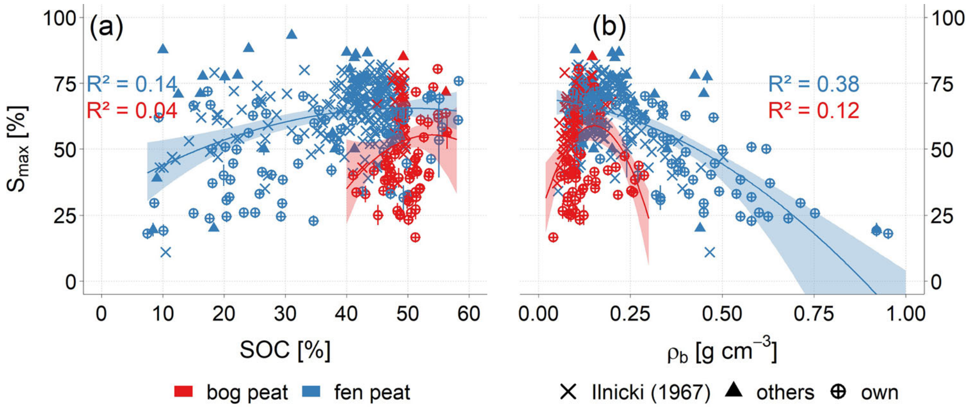

FIGURE 4 Maximum shrinkage (S_{max}) in dependence on (a) soil organic carbon content (SOC) and (b) bulk density (ρ_b). Error bars represent standard errors (for points without error bars, standard error is not given or determinable), ribbons depict the 2.5% and 97.5% quantiles. Parameters of fitted regression lines are listed in Table S5.

despite similar SOC contents. The "graminoid" class (e) comprises peats containing different graminoid species (Table 4) in different volumetric shares which is expected to influence shrinkage behavior. "Moss and graminoid" peats (d) showed the same issue enhanced by varying shares of mosses which, as discussed above, strongly influence shrinkage behavior in dependence of the degree of decomposition. The different stabilizing effects of fibric and hemic moss remains can be an explanation for the large scatter and the poor fit for the "moss" class which furthermore shows only a small range of SOC contents for the majority of samples (c). By testing for significant differences of S_{max} values of the substrate classes between data origin, we found that (only) the S_{max} values of moss peats differed significantly. This might be ascribed to the fact that the majority of the investigated samples originated from either Polish or Northwest German bogs which might show structural differences due to differing climate conditions in present and history (Joosten et al., 2017). Furthermore, Ilnicki (1967) only took samples from below the groundwater level which may have led to an underrepresentation of upper soil horizons which might show a different shrinkage behavior.

Ilnicki (1967) divided his data set into peats with and without mosses and found a significant negative linear correlation between S_{max} and AC for peats without mosses, whereas peat samples with mosses did not show any correlation with AC. This confirms the patterns shown in Figure 4a and Figure 5, where AC were converted into SOC and consequently the relations for soils without mosses, inclusive mixed peats but except wood peats, were positive but very weak.

As discussed above, ρ_b could be more suitable to explain values of S_{max}. Overall, this seemed to be true to some degree for all fen peats combined (Figure 4b, $R^2{}_{\rho b}$ = 0.38, $\mathrm{RMSE}_{\rho b}$ = 11%). S_{max} was decreasing with increasing ρ_b and in turn decreasing pore sizes. For bog peat soils, the relation between S_{max} and ρ_b was also stronger than between S_{max} and SOC but still weak ($R^2{}_{\rho b}$ = 0.12, $\mathrm{RMSE}_{\rho b}$ = 15%). The shape of the fitted curve for bog peat soils is in line with the pattern shown in Figure 3a. For ρ_b below 0.15 g cm^{-3} (fibric to hemic soil) S_{max} is increasing with increasing ρ_b. For higher values which represent hemic to sapric soils S_{max} is decreasing with increasing ρ_b. The large spread of S_{max} values of bog peat soils, especially of moss substrate (Figure 6c) with ρ_b values below 0.12 g cm^{-3} could be ascribed to the significant differences in S_{max} of fibric and hemic *Sphagnum* remains, as discussed above. According to Table S4, there is an overlap of ρ_b in the definition of fibric and hemic peat. Hence, there were moss containing peats with similar values of ρ_b, in the range of 0.07–0.1 g cm^{-3} but different structural properties which strongly influence S_{max}.

The quality of the proposed regressions using ρ_b strongly depends on the substrate (Figure 6). Similar to the relations between S_{max} and SOC (Figure 5), $R^2{}_{\rho b}$ is much higher for organo-mineral soils (a) and wood peat (f) (0.74 and 0.46, respectively) than for the other substrates. S_{max} of organo-mineral soils decreased with increasing ρ_b which can be ascribed to decreasing porosity. S_{max} of wood peat increased slightly up to ρ_b of around 0.2 g cm^{-3} and decreased for higher ρ_b values, confirming the pattern observed for SOC.

For amorphous substrates (b), the relation of S_{max} to ρ_b is stronger ($R^2{}_{\rho b}$ = 0.28) than to SOC. S_{max} is decreasing linearly with increasing ρ_b and correspondingly decreasing porosity. However, the scatter of S_{max} values is large due to the large heterogeneity within this substrate class. The other substrate classes again showed very low values of $R^2{}_{\rho b}$ of around 0.1 due to, in principle, the same issues discussed above (pooling of peat samples with different shares of different plant remains, degree of decomposition and history). Moss containing peats ("moss" (c) and "moss and graminoid" (d)) showed S_{max} values that first increased with increasing ρ_b (up to 0.12 g cm^{-3} and 0.17 g cm^{-3}, respectively) and decreased for higher ρ_b values. As the highest values of S_{max} occur within the ρ_b

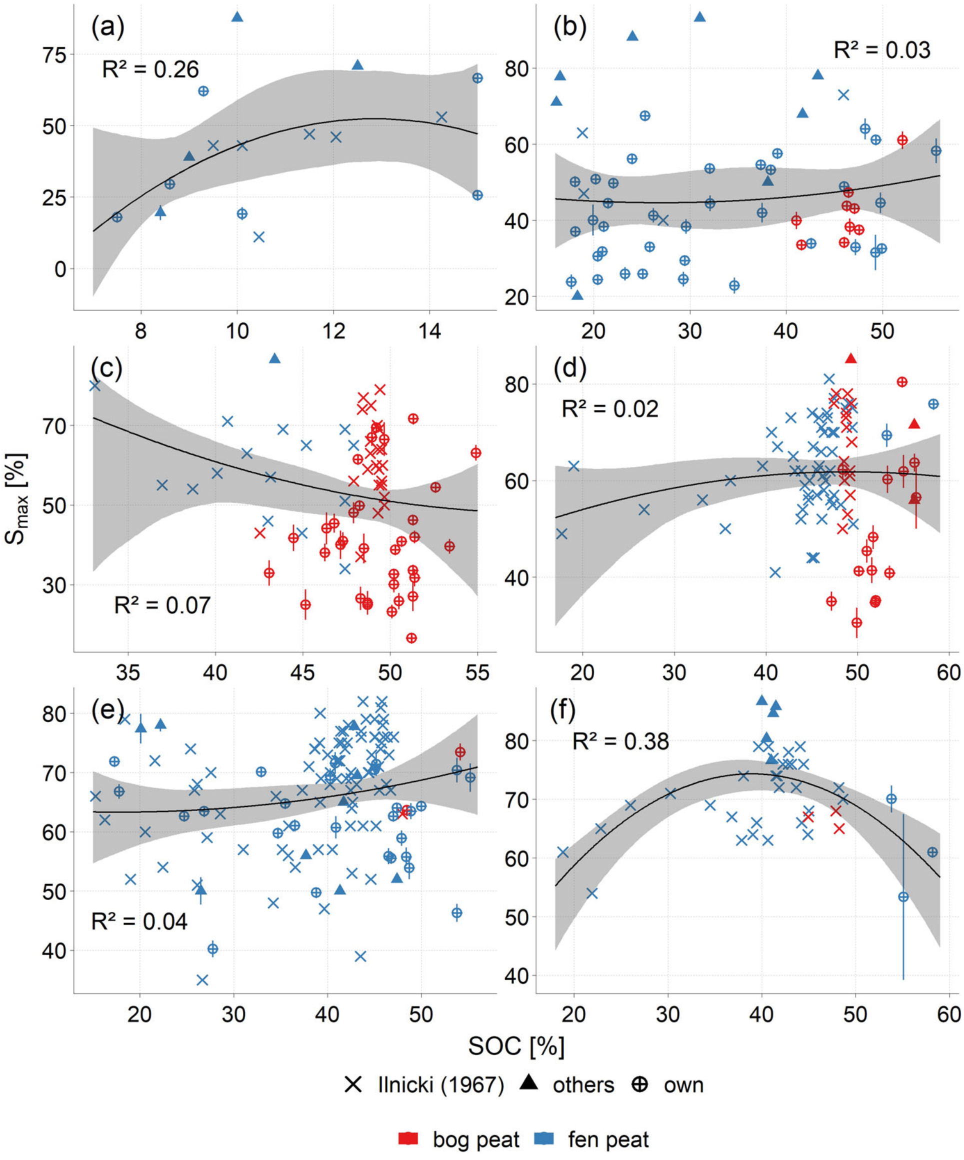

FIGURE 5 Maximum shrinkage (S_{max}) in dependence on soil organic carbon content (SOC) for (a) organo-mineral soil, (b) amorphous peat, (c) moss peat, (d) moss and graminoid peat, (e) graminoid peat, and (f) wood peat. Error bars represent standard errors (for points without error bars, standard error is not given or determinable), ribbons depict the 2.5% and 97.5% quantiles. Note individual axis scaling. Parameters of fitted regression lines are listed in Table S6.

range of hemic peat (0.07 g cm^{-3} ≤ ρ_b < 0.2 g cm^{-3}) this confirms the effect of the decomposition of moss remains on shrinkage. However, due to the limited number of data points, the decreasing branch of the curve should not be overinterpreted. Graminoid peats (e) showed a slight decrease of S_{max} with increasing ρ_b and correspondingly decreasing porosity.

For soils with $\rho_b \leq 0.2$ g cm^{-3}, Päivänen (1982) found positive logarithmic relationships between S_{max} and ρ_b for moss (*Sphagnum*), graminoid (*Carex*), and wood peats. In the case of moss and wood peats these results fit well to our results, but only for ρ_b values below 0.12 g cm^{-3} and 0.2 g cm^{-3}, respectively. For graminoid peats (incl. *Carex*) we found a (very weak) linear negative relationship, instead. However, data of this study could not be included into the meta-analysis as results were averaged over the whole range of degrees of decomposition (see part I and Table S1).

For ρ_b, Ilnicki (1967) found that the correlation for peats without mosses was negative and clearer than for peats with mosses, which showed a positive correlation. This largely confirms the patterns shown in Figures 4b and 6 where substrates without mosses except wood peat show negative relationships whereas substrates with mosses plus wood peat show positive relationships up to certain ρ_b values and negative ones for higher ρ_b values.

As discussed above, the heterogeneity of the data used in this study and the need for interpreting peat descriptions might have contributed to the relatively poor fit of the regression

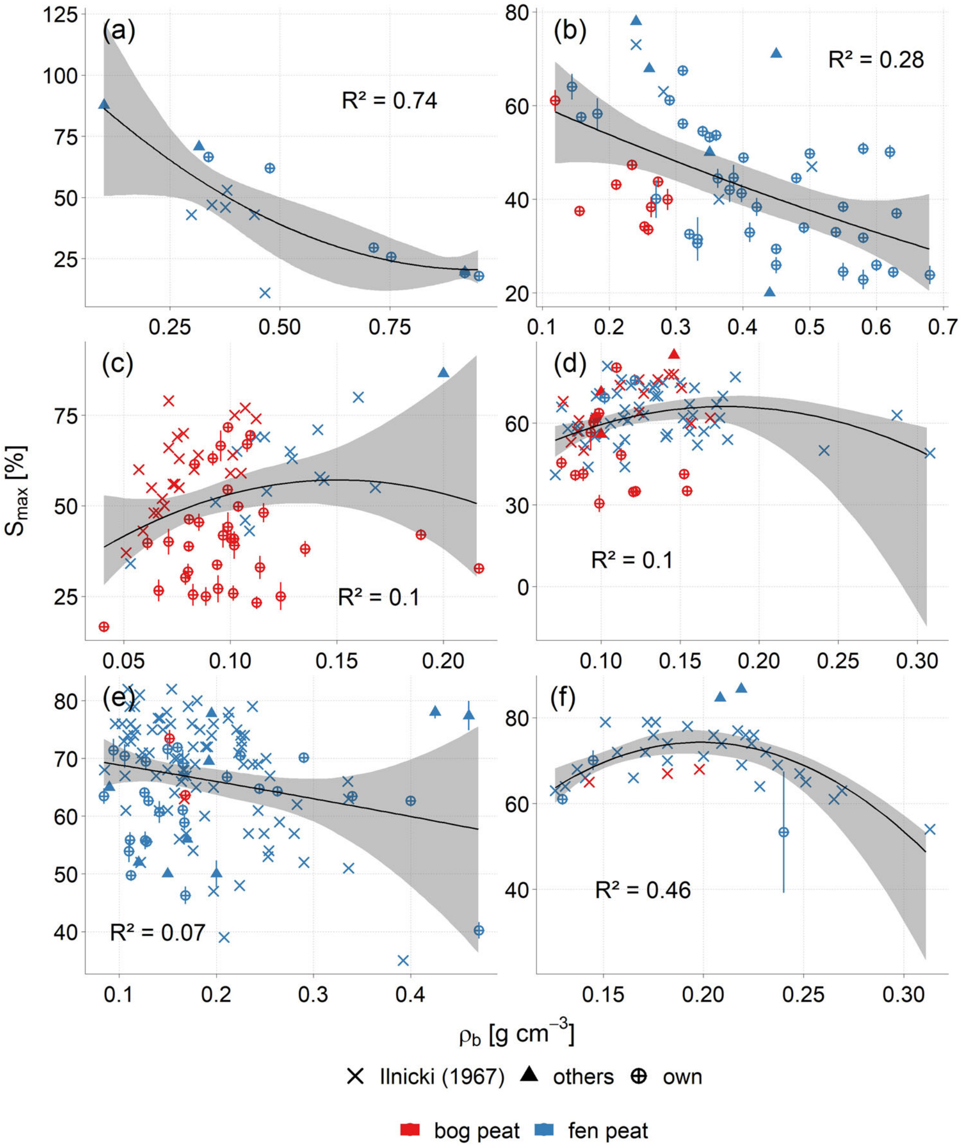

FIGURE 6 Maximum shrinkage (S_{max}) in dependence on bulk density (ρ_b) for (a) organo-mineral soil, (b) amorphous peat, (c) moss peat, (d) moss and graminoid peat, (e) graminoid peat, and (f) wood peat. Error bars represent standard errors (for points without error bars, standard error is not given or determinable), ribbons depict the 2.5% and 97.5% quantiles. Note individual axis scaling. Parameters of fitted regression lines are listed in Table S6.

equations. The analysis of the data from our own measurements only showed generally the same patterns (Seidel et al., 2023). The regressions determined for SOC were slightly better which can, at least in parts, be explained by the fact that a conversion between AC and SOC or ρ_b was not necessary. However, there are uncertainties regarding the moisture state at which ρ_b is related to. As described above, our own measurements are related to saturated volume. For few of the other data points this is not clearly known ($n = 5$) or ρ_b had to be estimated by applying the empirical equation from Wittnebel et al. (2021) shown above ($n = 7$). Ilnicki (1967) used the fresh (field conditions) volume as reference which in this case can be assumed equal to saturated volume as he only took samples from below the groundwater level. This choice of samples might be one reason for the significant differences in S_{max} values of moss peat (Figures 5 and 6c) measured by him and by us as he predominantly took samples from deeper layers which could show different shrinkage behavior (probably larger S_{max}) than samples from the upper layers which are not permanently saturated and have thus probably experienced several shrinkage-swelling cycles.

3.2.3 | Implications for the determination of soil parameters

As addressed in the introduction, shrinkage affects volume-based soil properties which were determined in laboratory and commonly referred to volume at saturation or at field conditions. This is illustrated by the following examples: We assume a peat with $S_{\max}$ of 70%, ρ_b of 0.10 g cm^{-3}, and a porosity at saturation of 95%. Given these values, the theoretical range of ρ_b from saturation to oven drying is 0.10 g cm^{-3} to 0.33 g cm^{-3} ($\rho_b/(1 - \mathrm{S}/100)$, with shrinkage S). Thus, if ρ_b is determined with samples which are not fully saturated and have already been shrinking, ρ_b is overestimated. Shrinkage is also affecting θ_v. If we assume S of 55% at a θ_v of 15%, θ_v would be 33% ($\theta_v/(1 - \mathrm{S}/100)$) instead of 15%. Following this, determined soil water retention characteristics can deviate from real properties of the soil (Horn et al., 2014; Schindler et al., 2015; Schwärzel et al., 2002; Szatylowicz et al., 1996). This also influences parameters which are derived from the water retention characteristics as the AWC, which is overestimated if shrinkage is not considered. Thus, it should be intended to account for shrinkage at the determination of soil water retention characteristics or at least one should be aware of the possible bias, especially if values from different studies are compared some of which accounted for shrinkage but others have not.

Since porosity and θ_v are influenced by shrinkage, the effect of shrinkage on WFPS is more complex. Generally, shrinkage increases WFPS as porosity decreases with desiccation. For example, WFPS does not or only slightly decrease during normal or near-normal shrinkage, where the loss of soil volume (equal to loss of pore volume) equals the lost water volume. Thus, the underestimation of WPFS (if shrinkage is neglected) will be greatest for soils which show marked (near-) normal shrinkage. During subnormal, structural, and residual shrinkage, where the loss of water exceeds the reduction of soil and pore volume, the underestimation of WFPS is less pronounced. Since supernormal shrinkage, where soil volume reduction exceeds water loss, usually occurs when soil moisture and WFPS are very low, the effect on WFPS is also low.

Since microbial processes depend on WFPS (Säurich et al., 2019), this is highly relevant for the interpretation of greenhouse gas flux data from organic soils and might also explain variability within and between studies.

These examples show the possible issues and biases (e.g., overestimation of ρ_b, underestimation of θ_v, and WFPS) at the determination of volume-based soil properties. Research studies should thus refer to the moisture state (e.g., saturated and field moist) of the sample at the determination of the reference volume and consider shrinkage during the determination of soil hydraulic properties.

4 | CONCLUSIONS

Shrinkage behavior of organic and mineral soils differs strongly. Since there is a gradual transition between these two soil groups there is a transition in shrinkage behavior, too. Degraded, organo-mineral or amorphous peat soils can behave similar to clay containing soils or they can show supernormal shrinkage which is not known for mineral soils but for peats. The shape of the SSC of an organic soil can depend on the applied volume and moisture metrics and the volume measurement approach. Thus, a direct analysis of SSCs from literature was not possible due the different metric combinations, which are generally not convertible into each other without additional information. However, as shrinkage affects the quality of laboratory-determined volume-based soil properties (e.g., ρ_b, θ_v, AWC, and WFPS), it is very important to know the SSC as shrinkage does not proceed linearly for most soils. Additionally, it would be of great interest for further investigations to relate features of SSCs and parameters of shrinkage models to soil properties which are easier to determine (e.g., ρ_b, degree of decomposition, and botanical composition)

Most shrinkage models are very flexible in parametrization. Thus, some models which were developed for mineral soils could also be parameterized for organic soils. However, the flexibility also limits transferability, and no attempts have so far been made to derive parameters of shrinkage models from peat properties.

$S_{\max}$ depended on the degree of decomposition, peat substrate, peat type, and ρ_b. Poorly decomposed (fibric) rigid moss remains stabilized the pore structure and reduced $S_{\max}$. $S_{\max}$ of hemic and sapric soils (thus without rigid moss remains) was limited by their content of organic or mineral fine material and the associated shrinkable pore-space and the frequency and intensity of previous shrinkage and swelling. Graminoid and wood peats showed the highest values of $\mathrm{S}_{\max}$ which could be attributed to the lack of a stable matrix and sufficiently low ρ_b values to keep a large shrinkable pore-space.

SOC alone was only a weak predictor for shrinkage although it is linked to degree of decomposition, substrate, and ρ_b, which is a better predictor for $S_{\max}$. However, $S_{\max}$ values showed large scatter over all classifications and relations. This could, at least in parts, be attributed to the applied classifications and necessary interpretation of peat descriptions and conversions, especially from AC to SOC and from different types of degree of decomposition (e.g., von Post or from ρ_b and θ_g at saturation) to the fibric-hemic-sapric scheme.

While it could be ascertained that the shrinkage behavior of organic soils was strongly influenced by the presence and stability of *Sphagnum* remains, further, more homogenous data, is needed to derive robust shrinkage models for different types of organic soils. Besides the great importance of these models for the correction of volume-based soil properties they can help to disentangle physical and biological processes which contribute to subsidence and to determine CO_2 emissions from drained peatlands.

AUTHOR CONTRIBUTIONS

Ronny Seidel: Data curation; formal analysis; investigation; methodology; software; visualization; writing—original draft. **Ullrich Dettmann**: Conceptualization; funding acquisition; methodology; project administration; supervision; writing—review and editing. **Bärbel Tiemeyer**: Conceptualization; funding acquisition; methodology; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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