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# Hydro-physical and carbon properties of peat across peatland types and climate zones

Ji Qi [a], Sophia Weigt [a], Miaorun Wang [a], Fereidoun Rezanezhad [b], William Quinton [c], Dominik Zak [d], Sate Ahmad [e], Lingxiao Wang [f], Ying Zhao [g], Bernd Lennartz [a], Haojie Liu [a,*]

[a] Faculty for Agriculture, Civil and Environmental Engineering, University of Rostock, Justus-von-Liebig-Weg 6, 18059 Rostock, Germany
[b] Ecohydrology Research Group, Department of Earth and Environmental Sciences and Water Institute, University of Waterloo, Waterloo, Ontario, Canada
[c] Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, Ontario, Canada
[d] Department of Ecoscience, Aarhus University, Aarhus, Denmark
[e] Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland
[f] School of Geographical Sciences, Nanjing University of Information Science & Technology, Nanjing 210044, China
[g] College of Resources and Environmental Engineering, Ludong University, Yantai 264025, China

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ABSTRACT

The hydro-physical properties of peat play a pivotal role in regulating the water, nutrient, and carbon cycles of peatland ecosystems. However, our understanding of peat hydraulic properties remains limited, especially at a global perspective. In this study, we compiled a comprehensive global database of the peat physical, hydraulic, and chemical properties, including bulk density (BD), porosity, macroporosity, saturated hydraulic conductivity ($K_s$), carbon content, and carbon density, encompassing tropical peatlands, boreal and temperate fens and bogs, and permafrost regions. Our primary objective was to examine how these properties varied along a BD gradient across peatland types and climate zones. The results revealed a robust linear relationship between carbon density and BD for various peatland types with carbon content exceeding 35 % ($R^2 > 0.93$, $p < 0.001$). The carbon density of tropical peatlands was more sensitive to changes in BD than that of boreal and temperate peatlands. Total porosity was found to decrease linearly as BD increased, while macroporosity followed a power-law relationship with BD. These trends were consistent across all peatland types, underscoring a strong and reliable association between BD and both total porosity and macroporosity. Additionally, $K_s$ exhibited a general decline with increasing BD, with the relationship characterized by log–log functions that varied among peatland types and climate zones. These findings indicated that hydraulic functions of peat (e.g., carbon density, $K_s$) were significantly influenced by the peat-forming vegetation such as woody plants, *Sphagnum*, sedges, and the prevailing climatic conditions of the peatland. This study demonstrated that the key peat hydro-physical–chemical parameters—including carbon density, porosity, macroporosity, and $K_s$ could be reliably estimated using the BD, with relatively high coefficients of determination ($R^2 > 0.4$), highlighting the critical importance of determining BD as a proxy for estimating other hydro-physical properties of peat when direct measurements are unavailable and potentially serving as reliable tools for estimating the carbon stock of peatlands across peatland types and climate zones.

## 1. Introduction

Peatlands cover about 3 % of the Earth's land surface, yet they store roughly 21 % of the world's soil carbon (Leifeld and Menichetti, 2018). Peatlands are distributed across various climate zones: in the temperate and boreal regions of the Northern Hemisphere, they primarily form under conditions of high rainfall and low temperatures, while in tropical regions such as Southeast Asia, Central and South America, and Africa, they develop in environments characterized by both high rainfall and high temperatures (Joosten and Clarke, 2002; Page et al., 1999, 2011; Xu et al., 2018). In northern peatlands, 43 % of soil carbon are stored in the form of permafrost, forming a thick layer crucial for global carbon

* Corresponding author.
*E-mail address:* haojie.liu@uni-rostock.de (H. Liu).

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sequestration and sensitive to climate (Hugelius et al., 2014; Heffernan et al., 2020).

Globally, approximately 12 % of peatlands have been artificially drained for agriculture, forestry, and peat extraction (UNEP, 2012). Peatland drainage induces aerobic conditions that lead to carbon mineralization and the emission of greenhouse gases such as carbon dioxide and nitrous oxide, damaging ecosystem functions and transforming peatlands from long-term carbon sinks into sources (Tiemeyer et al., 2016; Liu et al., 2019). Peatland drainage not only causes greenhouse gases emissions but also leads to changes in the hydro-physical and biogeochemical properties of peat (Price, 1996, 1997; Price and Schlotzhauer, 1999; Liu et al., 2019; Liu et al., 2020). Peatland drainage generally increases soil bulk density (BD), decreases total porosity, and alters the pore size distribution, although these effects can also be influenced by spatial variability (Wallor et al., 2018; Rezanezhad et al., 2010; Liu et al., 2019; Ahmad et al., 2025). Long-term intensive peatland drainage accelerates carbon mineralization, leading to substantial reductions in soil carbon content and a consequent increase in BD (Pronger et al., 2014; Tiemeyer et al., 2016; Liu et al., 2020). The BD is a crucial soil parameter of peat that can be used to estimate other biogeochemical and hydro-physical properties, such as total porosity, macroporosity, saturated hydraulic conductivity ($K_s$), nitrous oxide ($N_2O$) emissions, carbon content, carbon to nitrogen (C/N) ratio, and carbon density (Warren et al., 2012; Liu et al., 2019; Morris et al., 2022). BD also serves as an indicator of soil degradation, reflecting organic carbon mineralization and associated changes in the C/N ratio and pore structure—factors that influence oxygen availability, nitrogen cycling, and $N_2O$ emissions. Because it integrates these degradation-driven processes, BD is a practical predictor for large-scale $N_2O$ emission estimates in drained peatlands (Liu et al., 2019). While the correlation between BD and total porosity as well as macroporosity in boreal and temperate peatlands has been well established (Liu et al., 2020), it remains uncertain whether these relationships apply to tropical and permafrost peatlands.

Carbon density is a fundamental parameter for quantifying soil carbon stocks. Warren et al. (2012) developed a cost-effective method to estimate carbon density from BD in peat soils with organic carbon content exceeding 40 %, thereby significantly reducing the need for expensive laboratory analyses. Subsequent studies validated the reliability of this method in both intact and logged forest sites, though a revised equation was recommended for oil palm plantations (Farmer et al., 2014). Another approach, proposed by Rudiyanto et al. (2016), involves estimating soil carbon density by multiplying a constant average carbon content with BD, and has shown high accuracy across various land use types (Rudiyanto et al. 2016). Recently, Crouch and Chandler (2021) estimated peat carbon density in the Bamford WTW catchment (UK) using BD data. Despite these advancements, these relationships remain insufficiently validated for other peatland types, such as boreal and temperate bogs and fens, and permafrost peatlands.

The $K_s$ of peat is a vital parameter for understanding its water flow and solute transport capacity and is essential for hydrological processes in both saturated and near-saturated conditions in peatlands (Morris et al., 2022). $K_s$ is strongly influenced by the pore structure and degree of decomposition (Quinton et al., 2008; Morris et al., 2022), as well as the inherent heterogeneity and anisotropy of the peat's porous matrix (Beckwith et al., 2003; Rezanezhad et al., 2016; Wang et al., 2020). Determining $K_s$ in peatlands is further challenged by its spatial variability (Ahmad et al., 2020; Wang et al., 2021), the impacts of land use (Kurnianto et al., 2019), and microform type (*e.g.*, hollow and hummock; Morris et al., 2022). This variability makes field-scale $K_s$ measurements time- and resource-intensive. To address this, the pedotransfer functions (PTFs) have been developed for various peatland types, allowing $K_s$ to be estimated from more readily measurable peat soil properties. These PTFs incorporate parameters such as BD, macroporosity, peatland type (*e.g.*, bog and fen), microform type (hollow and hummock), and carbon to nitrogen ratio to estimate $K_s$ values (*e.g.*, Morris et al., 2015; Liu and Lennartz, 2019; Wang et al., 2020; Morris et al., 2022; Fewster et al., 2023). However, most of these PTFs formulated for predicting $K_s$ are based on data from boreal and temperate peatlands. It remains uncertain whether these functions perform reliably when applied to tropical or permafrost peatlands, which may differ significantly in their physical and hydrological characteristics.

In this study, we aim to investigate the relationship between BD and other soil hydro-physical–chemical properties across different climate zones and peat types. We compiled a comprehensive dataset of peat physical, hydraulic, and chemical properties, including BD, porosity, macroporosity, $K_s$, carbon content, and carbon density. These properties were categorized by geographical regions such as tropical, boreal and temperate, and permafrost zones. The dataset also distinguishes between different types of peatlands such as bogs and fens. The main objectives of this study are to: (1) examine the variation in peat hydro-physical properties in relation to BD, and (2) assess whether the relationships between BD and other hydro-physical properties differ across climate zones and peat types; and (3) evaluate the reliability of BD as a predictor of peat organic carbon density across various climate zones and peatland types.

## 2. Materials and methods

### 2.1. Data extraction

The Web of Science (https://www.webofscience.com) and Scopus (https://www.scopus.com) databases were searched for articles containing the terms "peat" AND "carbon content" OR "carbon density"; "peat" AND "porosity" OR "macroporosity" OR "soil water retention curve"; "peat" AND "saturated hydraulic conductivity" in the title, abstract, or keywords. The papers identified in this search were refined using the following criteria: (a) the study focused on peatlands in different climate zones (tropical peatlands, boreal and temperate peatlands, and permafrost peatlands) and included detailed descriptions of the study sites along with key physical properties of the peat soils—specifically, the availability of soil BD data was required and the peat carbon content had to exceed 12 % (Soil Survey Staff, 1999); (b) for boreal and temperate peatlands, only studies that reported the peat types (*e.g.*, bogs and fens) were considered. Although peatland type can vary with depth due to ecological succession (*e.g.*, from fen to bog), most studies did not provide detailed stratigraphic data or peat-type classification by depth. Therefore, in this study, peatland classification (bog or fen) was based on the ecological status of the sampling sites as reported in the original publications; and (c) the data collections were limited to soil depths within the top 1 m. Permafrost refers to ground that remains below 0 °C for at least two years (Obu et al., 2019). In the northern permafrost region—including continuous, discontinuous, and sporadic/isolated zones—approximately 1.7 million km$^2$ of peatlands are affected by permafrost (Hugelius et al., 2020; Palmtag et al., 2022). In this study, boreal and temperate bogs and fens are considered non-permafrost peatlands.

A total of 99 studies were selected for this research (Supplementary Table S1). A comprehensive dataset was developed to capture the physical and hydraulic properties of the investigated peats, including geographic coordinates and sample-specific variables such as carbon density ($n = 1421$), macroporosity ($n = 190$), total porosity ($n = 683$), and saturated hydraulic conductivity ($K_s$, $n = 1083$), with all records also containing values for BD. Detailed information is provided in Supplementary Table S1 and the locations and distribution of the studied peatland sites for data sources are shown in Fig. 1. In this study, carbon content refers specifically to soil organic carbon. Accordingly, carbon density denotes soil organic carbon density. In cases where inorganic carbon is negligible, total carbon measurements are used for estimation purposes (Farmer et al., 2014; Crouch and Chandler, 2021; Dettmann et al., 2021). Carbon density values were obtained directly from original

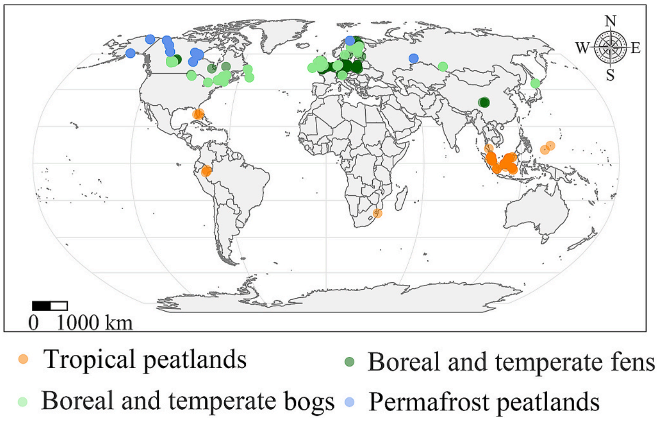


**Fig. 1.** The location and distribution of the studied peatland sites selected for synthesis data analysis.

data sources or derived from bulk density and carbon content measurements. For the $K_s$ dataset, both the measurement methods and site conditions (natural or drained) were recorded. The methods included laboratory techniques—permeameter, modified cube method, and multistep outflow; field techniques—permeameter, piezometer method, and auger holes; and the model-fitted method, which is distinct from both laboratory and field approaches. It is important to note that for permafrost peatlands, site condition data were not recorded, as their degradation primarily results from climate-induced warming rather than anthropogenic drainage.

### 2.2. Data processing and analysis

In cases where total porosity was not provided in the data sources, it was derived from bulk density and particle density values using (Eq. (1).

$$\varnothing = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \cdot 100\% \tag{1}$$

where $\varnothing$ is the total porosity (vol%), $\rho_{bulk}$ is the dry bulk density (g cm$^{-3}$), and $\rho_{particle}$ is the particle density (g cm$^{-3}$). Particle density was estimated based on soil organic matter content, using Equation (2) as described by Paquet et al. (1993) and Hallema et al. (2015), assuming particle densities of 1.55 g cm$^{-3}$ for organic matter and 2.65 g cm$^{-3}$ for the mineral fraction (Verdonck et al., 1978). In this equation, F represents the ratio of organic content to ash content.

$$\rho_{particle} = \frac{1+F}{(F/1.55)+(1/2.65)} \tag{2}$$

Macropore definitions in soil science vary widely, with reported equivalent diameters ranging from 30 to 3000 μm (Beven and Germann, 1982; Cameron and Buchan, 2006; Carter et al., 1994). In this study, macropores are defined as those with an equivalent cylindrical diameter greater than 30 μm, following the classification by Cameron and Buchan (2006). The pore size in soils can be estimated from the capillary rise equation (Bear, 1972). Assuming a contact angle of 52° for peat (Gharedaghloo and Price, 2019), a pressure head of –60 cm can be used to distinguish macropores. Macroporosity is then calculated as the difference between total porosity and volumetric water content at –60 cm $H_2O$ pressure head (Wang et al., 2021).

Carbon density was calculated using BD and carbon content, following the approach of Warren et al. (2012). It was also estimated using BD alone as a single predictor variable. In addition, carbon density was further estimated by combining BD with the average carbon content for each peatland type (tropical peatlands, boreal and temperate fens, boreal and temperate bogs, and permafrost peatlands). In this study, the $K_s$ values, obtained from laboratory or field experiments, exhibited a log-normal distribution. Consequently, $K_s$ values were transformed using a base-10 logarithm ($\log_{10}$) prior to further statistical analysis. A non-parametric Kruskal-Wallis test ('stats' package in R; R Core Team, 2024) was conducted to evaluate whether soil property parameters—such as carbon content, carbon density, porosity, and $K_s$—varied significantly among different climate zones and peatland types (tropical peat, boreal and temperate fens, boreal and temperate bogs, and permafrost peat). Post-hoc comparisons were performed using Dunn's test ('dunn.test' package in R; R Core Team, 2024) to determine which specific groups exhibited statistically significant differences.

## 3. Results

### 3.1. Carbon content

The carbon content dataset of the peat soils analyzed in this study spanned a wide range, from 12.0 % to 77.4 %. Tropical peatlands exhibited the highest carbon content (Supplementary Table S2). In tropical peat, boreal and temperate bogs, and permafrost peat, carbon content was predominantly above 40 % (Fig. 2). The median carbon content also varied across different peatland types. Tropical peatlands had the highest median carbon content at 51.6 %, followed by permafrost peatlands at 47.9 %, boreal and temperate bogs at 47.2 %, and boreal and temperate fens at 40.7 %. At a given BD, tropical peat generally had higher carbon content than the other three peatland types (Supplementary Fig. S1).

In boreal and temperate bogs and permafrost peat, carbon content showed a weak correlation with BD, with Pearson's correlation coefficients below 0.20 (Fig. 2c and 2d). In contrast, tropical peatlands and boreal and temperate fens exhibited moderate to strong positive correlation between carbon content and BD, with a Pearson's correlation coefficient of 0.37 and 0.72, respectively ($p < 0.01$; Fig. 2b).

### 3.2. Carbon density

The peat dataset analyzed in this study showed carbon density values ranging from 0.002 to 0.28 g cm$^{-3}$ (Supplementary Table S2), with boreal and temperate fens exhibiting the highest density. Average carbon densities for different peatland types were as follows: tropical peatlands (0.07 g cm$^{-3}$), boreal and temperate fens (0.06 g cm$^{-3}$), boreal and temperate bogs (0.04 g cm$^{-3}$), and permafrost peatlands (0.06 g cm$^{-3}$). The median carbon density of tropical peat was similar to that of fens and exceeded the values observed in bogs and permafrost peatlands.

The results revealed a strong linear relationship ($R^2 > 0.93$, $p < 0.001$) between carbon density and BD when soil carbon content exceeded 35 % (Fig. 3). Furthermore, the relationship between carbon density and BD varied significantly across different climate zones and peatland types. Notably, tropical peatlands displayed the highest slope in the carbon density versus BD functions. The results also indicated that applying the equation from Warren et al. (2012) to non-tropical peatlands substantially overestimates carbon density in boreal and temperate fens and bogs and permafrost peatlands.

This study adopted the method outlined by Rudiyanto et al. (2016) and demonstrated that estimating carbon density using BD and average carbon content for peat with carbon content greater than 35 % is highly reliable, yielding an $R^2 > 0.93$ and root mean square error (RMSE) values between 0.004 and 0.009 (Fig. 4).

### 3.3. Porosity and macroporosity

The porosity of peat soils varied widely, ranging from 47 vol% to 99 vol% (Supplementary Table S3). A strong negative liner relationship was found between the BD and total porosity (Fig. 5a; $R^2 = 0.77$, $p < 0.001$). The relationship between porosity and BD generally followed a single function across peat soils from different climate zones and peat types.

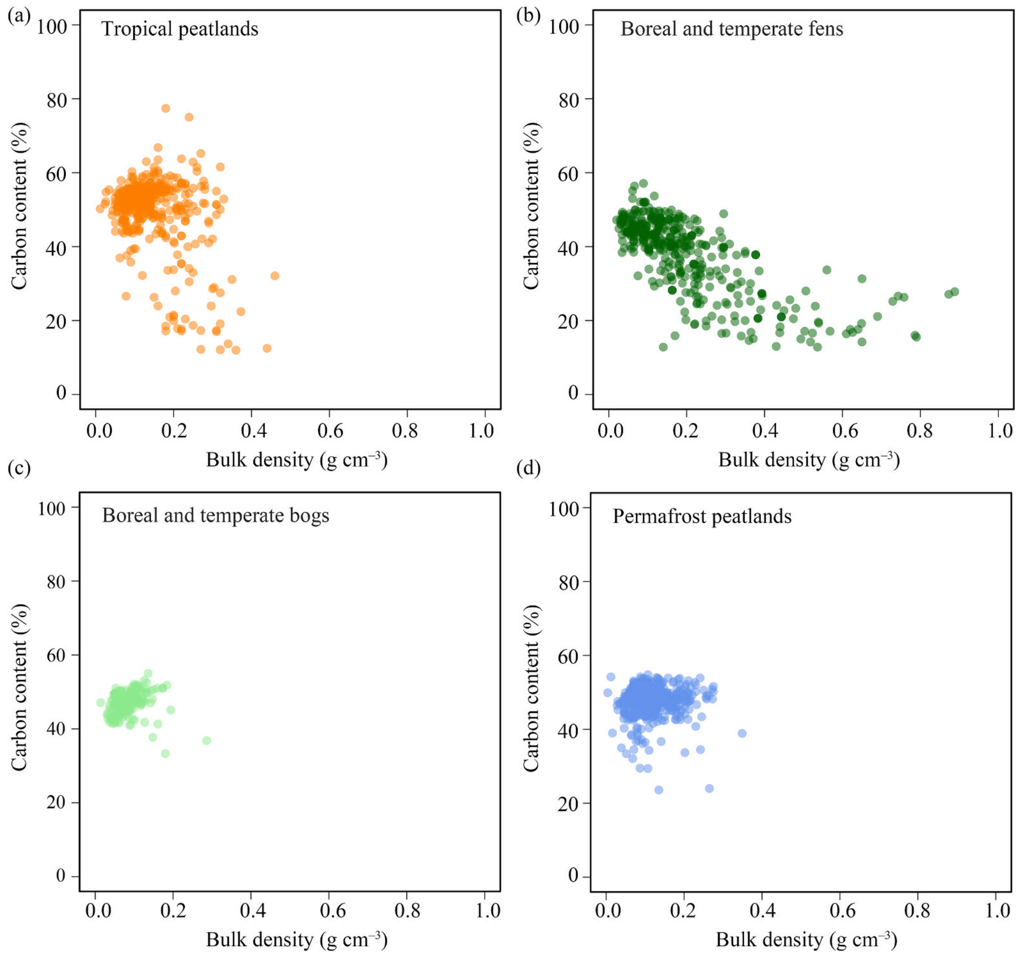


**Fig. 2.** Scatter plot of carbon content versus bulk density for peat soils from tropical peatlands (a), boreal and temperate fens (b), boreal and temperate bogs (c), and permafrost peatlands (d).

The macroporosity ranged from 1 vol% to 90 vol% and showed a significant decline as BD increased up to 0.2 g cm$^{-3}$ (Fig. 5b). Beyond this threshold, macroporosity remained nearly constant with further increases in BD. Peat soils with BD greater than 0.2 g cm$^{-3}$ were primarily found in boreal and temperate fens and permafrost peatland sites. When data from all peat soils were combined, a strong power relationship was observed between BD and macroporosity ($R^2 = 0.72, p < 0.001$; Fig. 5b). One outlier, indicated by a blue circle, was displayed but excluded from the model fit (Fig. 5b).

### 3.4. Saturated hydraulic conductivity

The relationship between $\log_{10}K_s$ and BD was best represented by logarithmic functions (Fig. 6), with variations in these functions observed among different peat types and the $\log_{10}K_s$ values ranged from –8.7 to –1.2 (Supplementary Table S4). In general, $K_s$ decreased with increasing peat decomposition and degradation, which was primarily driven by drainage (Fig. 6). At the same BD, the $\log_{10}K_s$ values for bogs were generally lower than those for tropical peatlands, fens, and permafrost regions. The average $\log_{10}K_s$ values for tropical peatlands, fens, bogs, and permafrost peatlands were –4.4, –4.7, –4.8, and –4.5, respectively. The median $\log_{10}K_s$ values for bogs were significantly lower compared to those observed in tropical peatlands and permafrost peatlands (Supplementary Table S4). For bogs and fens, $\log_{10}K_s$ decreased significantly as BD increased up to 0.2 g cm$^{-3}$ (Fig. 6b and 6c). However, for boreal and temperate fens with BD greater than 0.2 g cm$^{-3}$, no clear trend was observed and $\log_{10}K_s$ exhibited considerable variance.

The results also showed that the variance in $K_s$ values was influenced not only by BD but also by the anisotropic properties of peat soils. The regressions presented in Fig. 6 include both horizontal and vertical $K_s$ values. The anisotropy of $K_s$, defined as $\log_{10}(K_{sh}/K_{sv})$, varied from –1.4 to 2.2 (Fig. 7). No consistent trend in $K_s$ anisotropy was observed across the BD gradient. However, peat soils with relatively low BD (BD < 0.2 g cm$^{-3}$) exhibited high variability in anisotropy, while those with higher BD (BD > 0.2 g cm$^{-3}$) displayed lower variability in anisotropy.

## 4. Discussion

### 4.1. Carbon content dynamics along a bulk density gradient

Carbon content is a critical indicator of peatland condition and its carbon storage capacity. The average carbon content in tropical regions, found in our synthesis data analysis, was approximately 50 %, which is consistent with previously reported values ranging from 47 % to 52 % (Farmer et al., 2014; Warren et al., 2012; Rudiyanto et al., 2016). Data analysis in this study reveals a weak correlation between carbon content and BD for boreal and temperate bogs as well as permafrost peatlands (Fig. 2c, and 2d). In line with this finding, Rudiyanto et al. (2016) noted that carbon content stabilizes around 50 % with minimal variation when BD ranges from 0.01 to 0.25 g cm$^{-3}$. Conversely, when carbon content drops below 50 %, its relationship with BD becomes less distinct, showing a slight negative trend. BD primarily reflects soil compaction and mineral content, while carbon content is mainly influenced by organic matter inputs and decomposition dynamics. The unclear correlation between BD and carbon content could be attributed to several

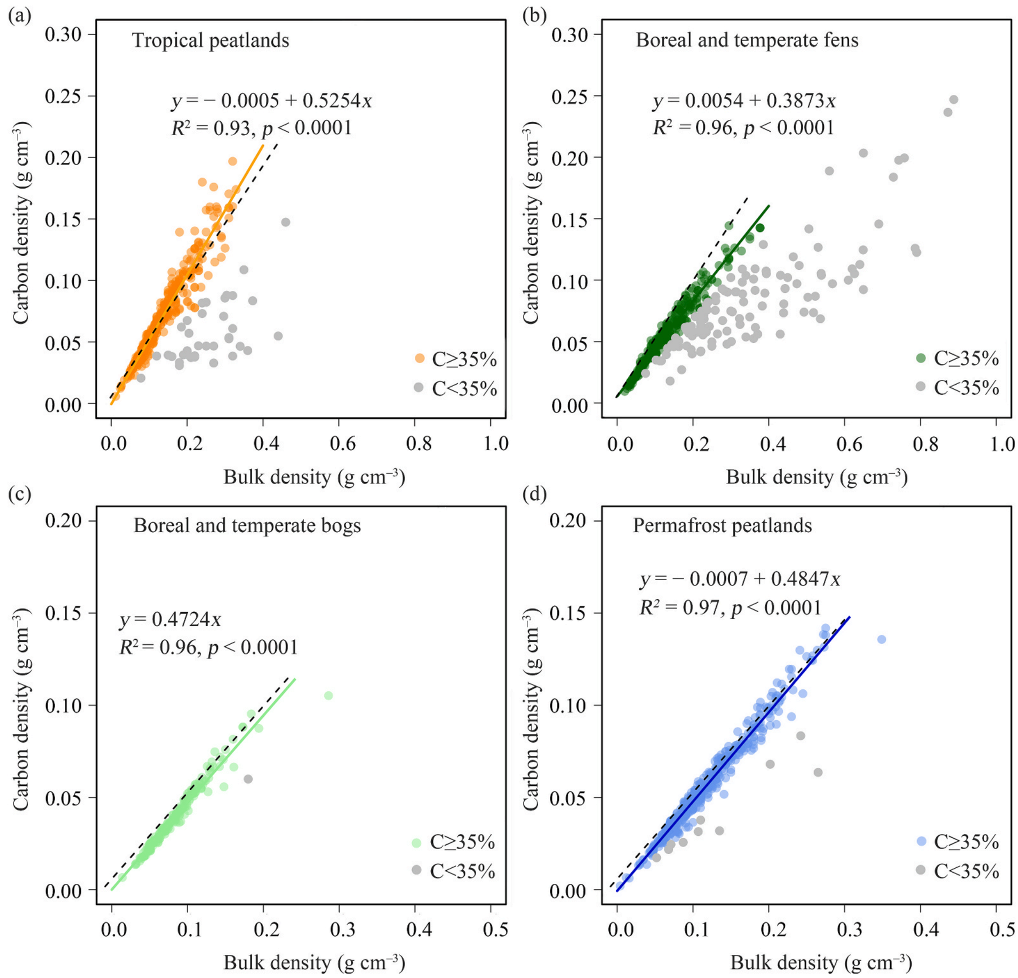


**Fig. 3.** Scatter plot of carbon density versus bulk density (g cm$^{-3}$) for peat soils with carbon content exceeding 35 %, categorized by ecosystem type: (a) tropical peatlands, (b) boreal and temperate fens, (c) boreal and temperate bogs, and (d) permafrost peatlands. Solid lines represent the regression models developed in this study, while dashed lines indicate the model based on Warren et al. (2012): Carbon density = Bulk density × 0.469 + 0.00582.

factors. For instance, the carbon and organic matter content of the original parent materials of peat (*e.g.*, *Sphagnum*, herbaceous plants, woody debris) vary significantly (Loisel et al., 2014; Chambers et al., 2011). Additionally, physical compaction resulting from the loss of peatland buoyancy during the initial stages of drainage can lead to an increase in BD without a corresponding short-term decrease in carbon content (Liu et al., 2020). As a result, BD might not serve as a reliable predictor for estimating carbon content in tropical peatlands, boreal and temperate bogs, or permafrost peatlands. In fens, lower carbon content levels (Fig. 2b) are primarily attributed to carbon mineralization following peatland drainage (Wang et al., 2021; Wittnebel et al., 2021; Fig. 6). During carbon mineralization, low-density carbon-rich materials are depleted and replaced by high-density components, such as mineral ash, leading to an increase in BD. Additionally, peatland drainage contributes to BD increases through peat shrinkage and compaction. Drainage-induced land subsidence, influenced by factors such as land use, drainage depth, and the duration of drainage, further complicates the relationship between BD and carbon content, introducing variability in their correlation (Hoyt et al., 2020; Adetsu et al., 2024; Liu et al., 2020).

### 4.2. Carbon density of peat

Carbon density is a critical parameter for accurately estimating carbon stocks in peatland ecosystems. Previous studies have demonstrated a strong linear relationship between soil carbon density and BD in soils with organic carbon content exceeding 40 % (Farmer et al., 2014; Rudiyanto et al., 2016; Warren et al., 2012). Consistent with these findings, this study indicates that soil carbon density can be reliably estimated from BD when the peat carbon content exceeds 35 % ($R^2 >$ 0.93), though model efficiency improves further beyond the 40 % threshold (Supplementary Table S5). However, the regression models (Fig. 3) vary significantly among peatland types. The regression analysis shows that tropical peatlands exhibit the steepest slope (0.53; Fig. 3a) in the BD-carbon density relationship, while fens display the gentlest slope (0.39; Fig. 3b). This suggests that carbon density in tropical peatlands is more sensitive to fluctuations in BD than in fens, highlighting the varying responsiveness of carbon storage in these ecosystems to changes in BD. This finding also indicates that applying the equation from Warren et al. (2012) to non-tropical peatlands leads to substantial overestimations of carbon density in boreal and temperate fens and bogs as well as permafrost peatlands (Fig. 3). This difference may be attributed to the variations in peat-forming processes (*e.g.*, organic matter accumulation and decomposition processes), localized ecological factors (*e.g.*, climatic influences, vegetation composition and hydrological conditions), and human activities (*e.g.*, soil compaction). For instance, tropical peat primarily consists of wood, roots, and unidentifiable organic matter, whereas boreal and temperate fens are predominantly characterized by sedges, and bogs are composed mainly of *Sphagnum* mosses (Apers et al., 2022; Crawford et al., 2024; McCarter et al., 2020; Rezanezhad et al., 2016). Fens, unlike bogs, receive water and nutrients from groundwater and surface runoff, leading to a more mineral-rich

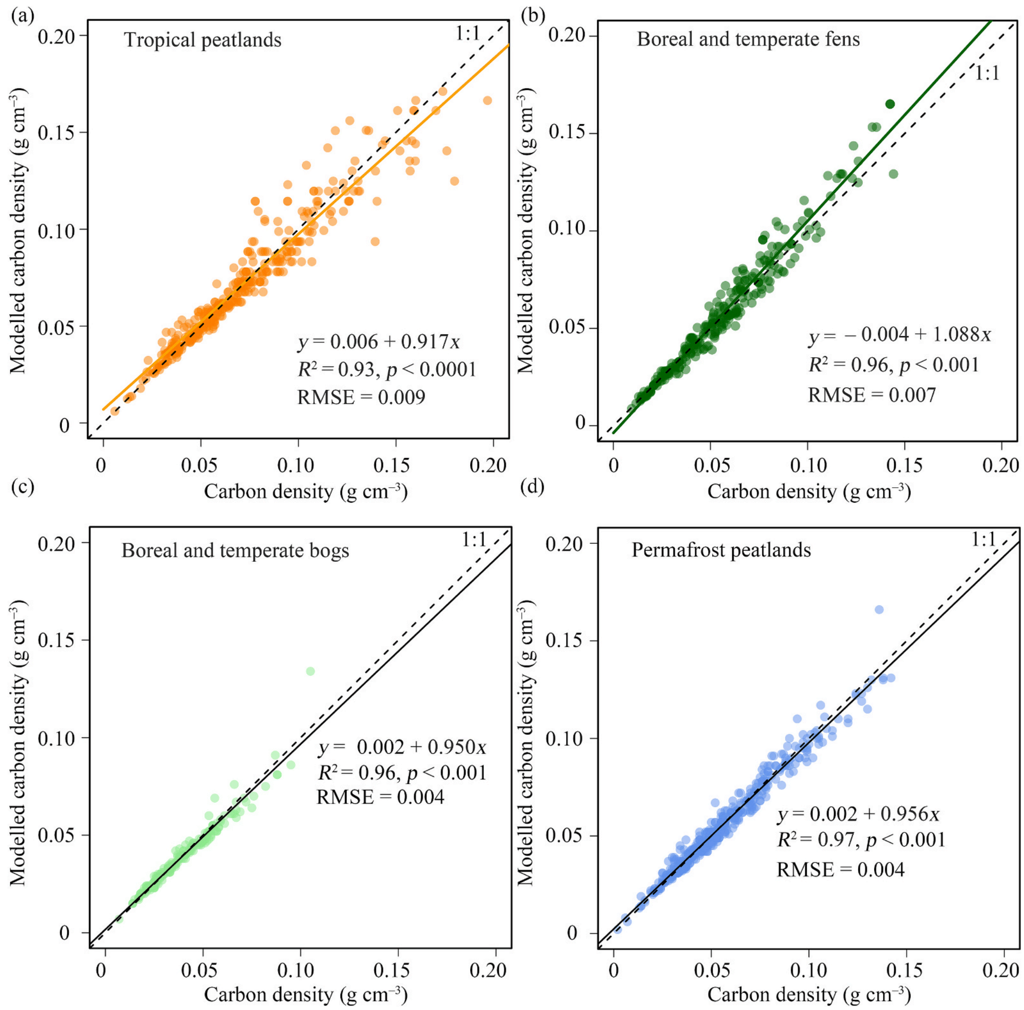


**Fig. 4.** Scatter plots comparing carbon density (calculated from bulk density and carbon content) with modelled carbon content (derived from bulk density and the average carbon content for each individual peatland type and climate zone), categorized by ecosystem types: (a) tropical peatlands, (b) boreal and temperate fens, (c) boreal and temperate bogs, and (d) permafrost peatlands. Model efficiency is assessed using the coefficient of determination ($R^2$) and the root mean square error (RMSE).

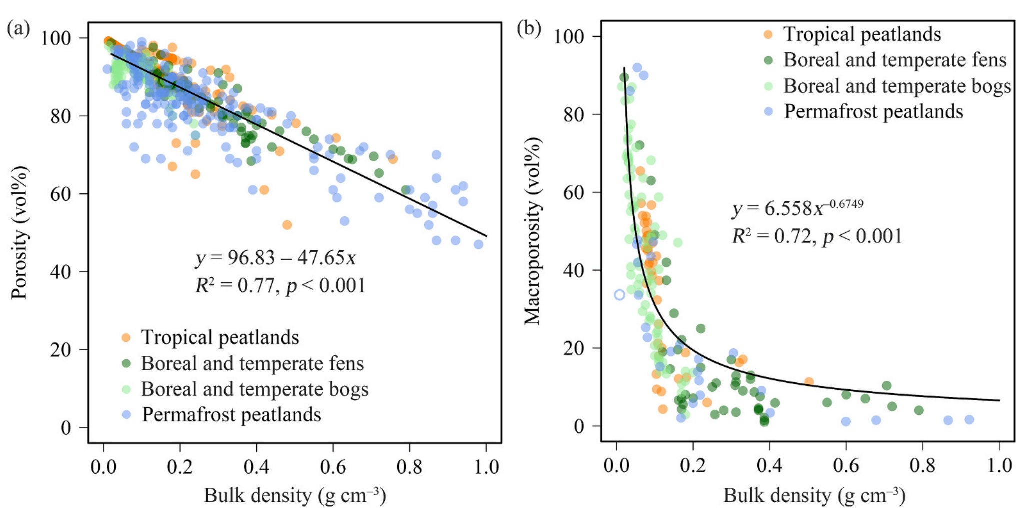


**Fig. 5.** Scatter plot showing (a) porosity and (b) macroporosity versus bulk density (BD) across different peatland types: tropical peatlands, boreal and temperate bogs, boreal and temperate fens, and permafrost peatlands. One outlier in the BD–macroporosity relationship, indicated by a blue circle, was excluded from the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

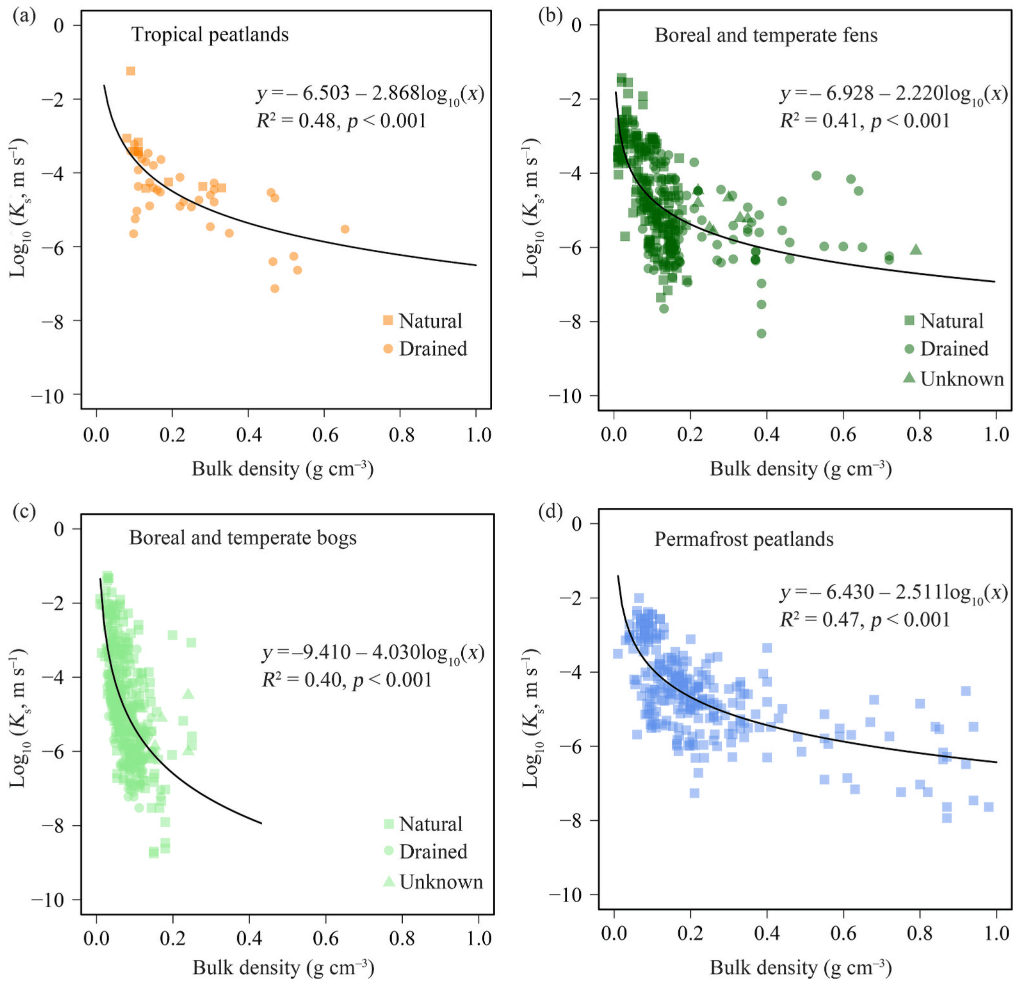


**Fig. 6.** Scatter plot of log-transformed saturated hydraulic conductivity ($\log_{10}K_s$) versus bulk density for different peatland types: (a) tropical peatlands, (b) boreal and temperate fens, (c) boreal and temperate bogs, and (d) permafrost peatlands. For tropical peatlands, boreal and temperate fens and bogs, peat samples are further categorized based on drainage history (natural vs. drained).

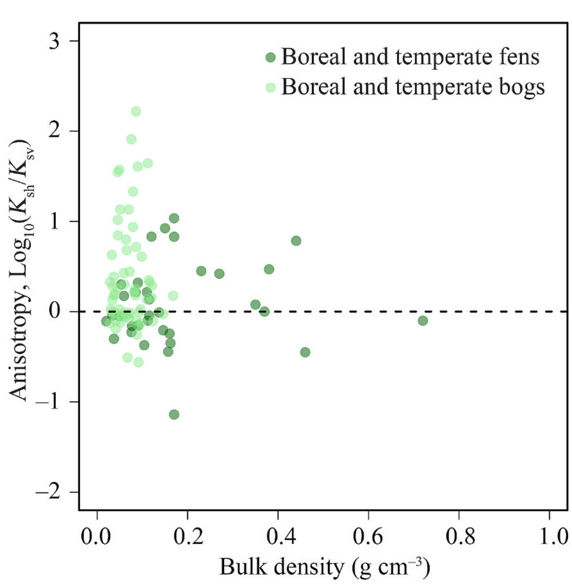


**Fig. 7.** Scatter plot illustrating the relationship between anisotropy of saturated hydraulic conductivity ($K_s$, m s$^{-1}$) and bulk density in boreal and temperate fens and bogs.

environment and a different composition of organic matter. This difference leads to variations in organic matter composition and, consequently, differences in BD and carbon density compared to bogs. Previous studies have shown that fens often have higher BD due to the accumulation of high decomposed organic matter (e.g., sedges) compared to the sphagnum-dominated peat of bogs (Loisel et al., 2014; Kurnianto et al., 2015). Moreover, the hydrological (groundwater-fed versus rainfed) and mineral particle fractions differences between fens and bogs influence the vertical distribution of organic matter, with fens exhibiting more stratified layers of peat with varying degrees of decomposition and mineral content (McCarter et al., 2020; Treat et al., 2016).

Rudiyanto et al. (2016) highlighted challenges in deriving carbon density using BD and carbon content due to: (1) the regression involving co-dependent variables (carbon content × BD vs. BD), which makes the slope estimate dependent on both carbon content and BD, with potential error correlations between measured BD and calculated carbon density; and (2) the inclusion of an intercept term that lacks physical significance. To address these issues, they proposed deriving carbon density using BD and average carbon content. While this method addresses some statistical concerns, it remains empirical. Mechanistic or physically based approaches for estimating carbon density are preferable and should be explored in future work. In this study, we adopted that approach and demonstrated its applicability across a wider range of peat samples with carbon content > 35 %. As shown in the Results (Fig. 4), the method performed well, despite slightly higher RMSE values compared to those reported by Rudiyanto et al. (2016). The slightly higher RMSE values compared to Rudiyanto et al. (2016) can be explained by two main factors: (1) greater variability in our dataset, with a standard deviation of carbon content of 0.05 compared to 0.02 in Rudiyanto et al. (2016), which increases model uncertainty; and (2) a wider data range, as we included all samples with carbon content > 35 %, while Rudiyanto et al. (2016) applied stricter criteria. When we applied their constraints, our RMSE decreased to ~ 0.005, consistent with their results. Thus, BD can serve as a valuable tool for estimating the carbon stock of peatlands across diverse peat types and climate zones. Nevertheless, it is crucial to acknowledge that the accuracy of BD estimations depends significantly on the methodologies used, which may introduce potential inaccuracies, particularly in the case of pristine peat (Dettmann et al., 2021; Dettmann et al., 2022; Weber et al., 2017).

### 4.3. Pore structure and saturated hydraulic conductivity

Previous studies have demonstrated a moderate to strong negative correlation between porosity and BD in peat soils (Oleszczuk and Truba, 2013; Menberu et al., 2021; Liu et al., 2020). Consistent with these findings, the present study found that porosity and BD exhibit a uniform linear relationship across different peat types (Fig. 5a). Notably, macroporosity decreased significantly as BD increased up to 0.2 g cm$^{-3}$; beyond this threshold, further increases in BD resulted in only marginal reductions in macroporosity (Fig. 5b). A power function was observed between BD and macroporosity, which can be supported by other studies (Liu et al., 2020; Wang et al., 2021). These findings demonstrate that the relationships between porosity, macroporosity, and BD are universally consistent, as they are effectively captured by generalizable functions across different peat types.

The movement of water in peat soils is governed by pore structure characteristics, including porosity, macroporosity, and pore connectivity (Liu et al., 2016; Rezanezhad et al., 2016; Soracco et al., 2019). Among these, macroporosity plays a critical role and has been shown to significantly correlate with $K_s$ in peat soils (Branham and Strack, 2014; Liu et al., 2020). In general, $K_s$ decreases as BD increases during decomposition and degradation processes. Peat degradation leads to soil shrinkage and compaction, which substantially reduce macroporosity and pore connectivity (Silins and Rothwell, 1998; Rezanezhad et al., 2010; Rezanezhad et al., 2016; Morris et al., 2015), thereby significantly lowering the $K_s$ of peat.

The $K_s$ of peat typically follows a log–log relationship with BD (Fig. 6), with a pronounced reduction in $K_s$ observed during the early stages of peat decomposition and degradation (BD < 0.2 g cm$^{-3}$). At this stage, $K_s$ is more sensitive to changes in soil physical structure caused by compaction or subsidence than to carbon mineralization processes (Fig. 2). In drained peatlands, the subsidence rate is reported to be approximately 5 cm year$^{-1}$ during the first 10 years following drainage. Thereafter, the average subsidence rate decreases to 0.5–2 cm year$^{-1}$, depending on factors such as drainage depth, land use, and the duration of drainage (Liu et al., 2020; Pronger et al., 2014). For highly decomposed and degraded peat soils (BD > 0.2 g cm$^{-3}$), a large variance in $K_s$ is observed (Fig. 6a and 6b). This variability is likely attributed to the formation of secondary macroporosity in the peat, such as root channels, earthworm burrows, and cracks (Liu and Lennartz, 2015; Liu et al., 2020; McCarter et al., 2020). In addition, the inclusion of both vertical and horizontal hydraulic conductivities in the regression analysis (Fig. 6) may have increased the observed variability by incorporating directional differences in $K_s$.

The relationship between BD and $K_s$ varies across peatland types (bogs or fens), suggesting that the original peat-forming plant materials also play a significant role in influencing the $K_s$ of peat (Morris et al., 2015; Morris et al., 2022). Our study indicates that when the BD is less than 0.04 g cm$^{-3}$, the $K_s$ of bogs and fens is comparable. However, when BD exceeds 0.04 g cm$^{-3}$, the $K_s$ of boreal and temperate bogs is generally lower than that of fens for a given BD (Fig. 6 b and 6c; Supplementary Fig. S2). Additionally, the $K_s$ of peat is also influenced by microhabitat types (e.g., hummocks vs. hollows; Morris et al., 2015, 2022), the methods used for $K_s$ measurement (Supplementary Fig. S3; Rosa and Larocque, 2008). However, the variability in $K_s$ associated with different measurement methods is further affected by factors such as the degree of peat degradation and soil depth, making it difficult to isolate and evaluate the methodological impact using currently available data (Morris et al., 2022). The direction of the measurements (Cunliffe et al., 2013) also contributes to the observed variability in $K_s$. For instance, data from the Arctic foothills of Alaska and the Scotty Creek permafrost peatlands (O'Connor et al., 2020; Ackley et al., 2021) demonstrated a strong log–log relationship between BD and $K_s$ (with $R^2 = 0.66$; $p < 0.001$). However, when data from Railway Bog were included, the correlation between BD and $K_s$ weakened ($R^2 = 0.47$; $p < 0.001$). One possible reason for this reduction in the strength of the relationship is the difference in sampling orientation: samples from the Arctic foothills of Alaska and Scotty Creek were collected vertically, while those from Railway Bog were collected horizontally (Fewster et al., 2023).

Anisotropy in peat soils arises from variations in pore distribution and connectivity (Liu et al., 2016). Sedges and reed communities uniquely form bedding planes based on litter orientation (Baird and Gaffney, 2000; McCarter et al., 2020). When reed litter aligns parallel to bedding planes, it creates large horizontal macropores with minimal vertical connectivity, resulting in higher horizontal $K_s$ than vertical $K_s$ (Baird and Gaffney, 2000). Conversely, vertically oriented wooden branches enhance vertical connectivity, leading to vertical $K_s$ exceeding horizontal $K_s$ (Liu and Lennartz, 2015; Liu et al., 2016; Wang et al., 2020). The anisotropy of $K_s$ varied significantly (from –1.4 to 2.2) in less decomposed and degraded peat soils (*e.g.*, BD < 0.2 g cm$^{-3}$; Fig. 7), highlighting the importance of considering anisotropic behavior in hydrological models in less disturbed peatland. The relative permeability in different directions governs both vertical and horizontal water flow within these ecosystems, and understanding this variability is crucial for accurately predicting water movement, retention, and solute transport dynamics in peatland hydrology. In contrast, highly degraded peat (higher BD), characterized by compacted structures and reduced pore connectivity, showed a small variance in $K_s$ anisotropy (Fig. 7), compared to its spatial heterogeneity (generally spanning two orders of magnitude). This finding suggests that in more degraded peat soils, the diminished functionality of pore structures, coupled with reduced variability in macropore distribution, significantly weakens the influence of anisotropic behavior. Instead, spatial heterogeneity in pore structure and connectivity becomes more critical for controlling water dynamics. The anisotropy of $K_s$ in tropical and permafrost peatlands has not been studied, highlighting the need for further research in this area.

## 5. Conclusions

Our study reveals that the key hydro-physical properties of peat—carbon density, porosity, macroporosity, and saturated hydraulic conectivity —can be reliably estimated using only a single soil physical parameter: bulk density. However, estimation functions vary among peat types, primarily due to differences in the original parent plant materials, such as wood, sedge, and moss. We identified a strong linear relationship between carbon density and BD across peat types with carbon content greater than 35 %, providing a reliable method for estimating peatland carbon stocks.

Porosity and macroporosity showed consistent negative correlations with BD, influencing $K_s$ significantly. Although the log–log relationship between BD and $K_s$ is evident, variability increases in highly decomposed peat due to secondary macroporosity formation and sampling orientation, complicating predictions. Additionally, anisotropy in $K_s$ —affected by pore structure and the alignment of organic materials—introduces further challenges for hydrological modeling. Overall, this global analysis quantifies BD–property relationships across climates and peat types, providing transferable functions for carbon stock estimation and hydrological modeling where measurements are lacking.

## CRediT authorship contribution statement

**Ji Qi:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Sophia Weigt:** Writing – review & editing, Methodology, Data curation. **Miaorun Wang:** Writing – review & editing, Methodology, Data curation. **Fereidoun Rezanezhad:** Writing – review & editing, Data curation. **William Quinton:** Writing – review & editing, Data curation. **Dominik Zak:** Writing – review & editing, Data curation. **Sate Ahmad:** Writing – review & editing, Data curation. **Lingxiao Wang:** Writing – review & editing. **Ying Zhao:** Writing – review & editing. **Bernd Lennartz:** Writing – review & editing. **Haojie Liu:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

## 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.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2025.117480.

## Data availability

The database necessary to reproduce the work is available from https://data.mendeley.com/datasets/3pm25vwxz6/1.

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