SOIL SCIENCE ANNUAL
2024, 75(4), 195241

https://doi.org/10.37501/soilsa/195241

Origin, transformation and classification of organic soils in Poland

Andrzej Łachacz[1*], Adam Bogacz[2], Bartłomiej Glina[3], Barbara Kalisz[1], Łukasz Mendyk[3], Mirosław Orzechowski[1], Sławomir Smólczyński[1], Paweł Sowiński[1]

[1] University of Warmia and Mazury in Olsztyn, Department of Soil Science and Microbiology, Plac Łódzki 3, 10–727 Olsztyn, Poland
[2] Wrocław University of Environmental and Life Sciences, Institute of Soil Science, Plant Nutrition and Environmental Protection, ul. Grunwaldzka 53, 50–375 Wrocław, Poland
[3] Poznań University of Life Sciences, Department of Soil Science and Microbiology, ul. Szydłowska 50, 60–656 Poznań, Poland

* Corresponding author: prof. dr hab. Andrzej Łachacz, andrzej.lachacz@uwm.edu.pl, ORCID iD: https://orcid.org/0000-0003-2902-2767

Received: 2024-08-08
Accepted: 2024-10-25
Published online: 2024-10-25
Associated editor: Cezary Kabała

Keywords:

Peat
Gyttja
Mud
Mursh
Soil Classification
Soil of the Year

Abstract

The Soil Science Society of Poland has selected organic soils (in Polish: *gleby organiczne*) as their *Soil of the Year 2024*. Organic soils consist of materials that contain ≥12% organic carbon (C), and include peat, gyttja and mud materials, as well as forest (leaf and woody debris) or meadow (grass debris) litter (≥20% organic C if saturated with water for <30 consecutive days a year). The specific properties of these soils, primarily the high organic C content, low bulk density and high porosity values, determine their disaggregation from mineral soils. In the 6th edition of the Polish Soil Classification (SGP 6), four main types of organic soils were distinguished: peat soils (in Polish: *gleby torfowe*), mursh soils (in Polish: *gleby murszowe*), limnic soils (in Polish: *gleby limnowe*) and folisols (in Polish: *gleby ściółkowe*). The estimated cover of organic soils in Poland ranges from 4 to 5% of the land surface, located mainly in closed depressions and river valleys; an exception are the folisols that mainly occur in mountain areas. Among organic soils, peat and mursh soils cover the largest area and are mainly used for agricultural purposes. Organic soils are considered the largest natural terrestrial reservoir of organic C, but disturbance to peatlands from climate change and human activities has impacted their C storage potential. In this review paper, we present (a) the concept of organic soils in Poland; (b) the classification scheme for organic soils in Poland and their correlation with international classification systems, such as the World Reference Base (WRB) and the NRCS Soil Taxonomy; (c) a review of the distribution, land use, threats and protection of organic soils in Poland; and (d) future research needs with regard to organic soils.

1. Introduction

Since 2018, the Soil Science Society of Poland has selected a *Soil of the Year*, an initiative intended to raise public awareness of the role and significance of soils. In 2024, the title was bestowed on organic soils. The 6th edition of the Polish Soil Classification (SGP 6, 2019) identified four types of organic soils (in Polish: *gleby organiczne*): peat soils (in Polish: *gleby torfowe*), mursh soils (in Polish: *gleby murszowe*), limnic soils (in Polish: *gleby limnowe*) and folisols (in Polish: *gleby ściółkowe*). As the name suggests, organic soils are made up of organic material that contains ≥ 12% organic carbon (C) if saturated with water for at least 30 consecutive days a year or ≥ 20% organic C if saturated with water for < 30 consecutive days a year (Kabała et al., 2019). A substantial accumulation of organic matter at the soil surface can stem from a high moisture content within the ecosystem and from specific weather conditions (low temperature, high precipitation), which slows down organic matter decomposition (mineralisation). In the temperate climate zone, which includes Poland, organic soil formation is mainly driven by water gathered from surrounding areas, which prevents oxygen from reaching the soil material, thereby creating the anaerobic conditions necessary for a positive soil organic matter balance. In SGP 6 (2019), the soils that develop if these hypoxic conditions are maintained have been classified as peat and limnic soils. The weather-dependent aspect of organic soil formation, on the other hand, is particularly well illustrated by the folisols that form in mountainous areas.

As they occupy the lowermost parts of the landscape (the borderline between land and water), organic soils play a very important role in the water, C and nutrient cycles (Joosten and Clarke, 2002; Rydin and Jeglum, 2006; Oleszczuk et al., 2008; Kimmel and Mander, 2010; Maljanen et al., 2010; Page and Baird, 2016; Kasimir et al., 2018; Norberg et al., 2018; Harris et al., 2022). The accumulation of organic matter (mainly in the form of plant remnants) in peatlands is a long-term process determined by climate, vegetation and the inundation processes that affect the edaphic factors in the catchment. Therefore, peat deposits are treated as living natural archives; a record of local environmental changes (e.g. Tobolski, 2000; Urban, 2004; Borówka et al., 2022; Okupny, 2023). Peatlands are unique in nature, different from both typical terrestrial and deepwater habitats, which is why they contribute to environmental diversity both in the geographical and biological sense. Thus, it comes as no surprise that peatlands and organic soils have drawn the interest of specialists from various fields, including ecologists, hydrologists, paleogeographers, paleobotanists and soil scientists. After all, untangling the functioning of complex peatland ecosystems requires coordinated interdisciplinary efforts.

A high organic matter content is the defining aspect of organic soils, influencing their environmental role. Organic soils also exhibit high total porosity values (up to 94%) and are water saturated under natural conditions (before drainage) (Zawadzki, 1970; Marcinek and Spychalski, 1987; Rezanezhad et al., 2016; Liu et al., 2020). In addition, as they contain substantial concentrations of biogenic elements, they are considered fertile and are widely used by farmers (Lucas, 1982; Everett, 1983; Ilnicki, 2002). They are also highly labile and susceptible to transformation through changes in hydrographic conditions (e.g. Okruszko, 1956, 1993; Marcinek, 1976; Marcinek and Spychalski, 1998; Oleszczuk et al., 2008, 2022; Leifeld et al., 2011; Krüger et al., 2015; Zając et al., 2018; Leifeld et al., 2020; Lasota and Błońska, 2021). The greatest threat to organic soils is posed by drainage, which triggers a cascade of changes in the soil matrix. Principally, increasing amounts of carbon dioxide (CO_2) are released to the atmosphere from the microbial decomposition of organic matter, while nutrients also seep into surface and groundwaters leading to increased levels of eutrophication (e.g. Tiemeyer et al., 2007; Oleszczuk et al., 2008; Kalisz et al., 2010; Tiemeyer and Kahle, 2014; Oleszczuk et al., 2022; Kalisz and Łachacz, 2023; Łachacz et al., 2023). As such, the condition of organic soils has drawn widespread interest from scientists, land users and the general public.

Organic soils in general, and the most common peat soils in particular, have long been of interest to humans. For centuries, peat has been burnt as a fuel, employed as a raw material by various industries, and converted into compost and used to grow garden plants and tree seedlings (e.g. Ilnicki, 2002; Joosten and Clarke, 2002). However, organic soils have been mainly used as grassland, for which they must first be drained. In Poland, approximately 75–80% of the peatland area has been drained for agriculture (e.g. Marcinek, 1978; Okruszko, 1993). Drained peat soils undergo a series of pedogenic transformations that are referred to as the mursh-forming process (Okruszko, 1960, 1993; Okruszko and Ilnicki, 2003; Łachacz et al., 2023). Accordingly, the resultant soils are termed mursh soils (SGP 6 2019; Kabała et al., 2019).

Although limnic soils (developed from organic mud or gyttja) cover a relatively small area of Poland, they are of particular interest. Gyttja soils are formed when lakes are rapidly drained, thereby exposing the lakebed (Łachacz and Nitkiewicz, 2021). Muddy soil forms from the addition of a silty mineral material deposited in river valleys and lake shores (Okruszko, 1969; Kalisz and Łachacz, 2008; Roj-Rojewski and Walasek, 2013). In river valley fen soils, muddy soils co-occur with alluvial soils of variable organic matter content (Kabała, 2022). Folisols cover a relatively small area of the country, mostly in the mountains, but they are important for the stability and functioning of those extreme environments.

The aim of this paper is to describe organic soils in Poland, profile them with the current edition of the Polish Soil Classification (SGP 6 2019), expound on the problems related to organic soil use and conservation, and finally propose directions for further research.

2. Organic soil studies in Poland

Interest in organic soils, especially peat soils, intensified in Poland in the second half of the 19th century due to the widespread use of peat for heating purposes. At the same time, reports of the agricultural use of organic soils, including peat soils, appeared in the scientific literature. Consequently, the term "mursh" (in Polish: *mursz*) emerged to describe drained and overdried peat soils (Strzemski, 1980). An important stage in the development of our knowledge of peatlands, including organic soils, was the research carried out in the interwar period in the current Belarusian part of the Polesie (Polesye) region, as part of preparations for land reclamation (i.e. drainage) and subsequent agricultural use of vast areas of peatland (Łachacz, 2024). This extensive research resulted in numerous publications and was summarised in a monograph by Kulczyński (1949), published first in Polish and then in English. During this era of peatland study, modern methods (for the time), such as palynological and plant macro-remains analyses, were used and focused on peatland water supply, the stratigraphy of the peat deposits, and the origin and division of peatlands.

Research on organic soils continued after the Second World War, which was reflected in the development of a peat classification scheme (Tołpa et al., 1967). Immediately after the war, there was a significant interest in peat deposits as an energy raw material, and the geological inventory of peat deposits in Poland was developed. This inventory covered peatland areas > 1 ha, with at least 30 cm of peat from the surface down and containing over 20% organic matter (Ilnicki, 2002). In this inventory, the use of organic soils for agricultural purposes, mainly as meadows and pastures, was taken into account. In the 1960s, the use of peat for heating purposes in Poland was completely abandoned, and peat soils were treated as agricultural land (Ilnicki, 2002). During this time, research also focused on the changes that organic soils undergo after drainage (e.g. Okruszko, 1956; Kowaliński, 1964; Marcinek, 1976).

Globally, land users and researchers have drawn attention to the significant changes that occur in organic soils due to drainage and agricultural use (e.g. Pons, 1960; Lucas, 1982, Everett, 1983; Ilnicki, 2002). These changes have been variously termed, for example, as secondary humification, secondary transformation or earthing (Grosse-Brauckmann et al., 1995; Łachacz and Kalisz, 2016, Łachacz et al., 2023). In Poland, the products (soil materials) of pedogenic transformations of originally wet organic materials were termed mursh (in Polish: *mursz*) (Miklaszewski, 1930; Tomaszewski, 1950, 1958; Strzemski, 1980), which was scientifically defined and described by Okruszko (1960, 1976), who used the term "muck" or "moorsh", although the English notation "mursh" is currently used (Kabała et al., 2019). It should be noted that the notation "mursh" had already appeared in the English translation of soil units in SGP 1 (1956) and SGP 2 (1959) and in Wondrausch (1963). Polish soil scientists have emphasised the evolutionary changes of shallow organic soils developed on sandy substrates (e.g. Rząsa, 1963; Mocek, 1978; Łachacz, 2001, Łabaz and Kabała, 2016; Łachacz et al., 2023; Łachacz and Załuski, 2023). An arenimurshic horizon (in Polish: *arenimurszik*) (SGP 6, 2019) is formed as a result of the mineralisation of soil organic matter and its amalgamation with the mineral sandy substrate. Depending on the organic C content, it is termed either semimurshic material (in Polish: *murszowaty*) or postmurshic material (in Polish: *murszasty*).

The research on the transformation of drained peat soils, initiated in the 1950s, was carried out at the Institute for Land Reclamation and Grassland Farming in Falenty, the "Biebrza" Research Station and at all agricultural universities (Łachacz and Kalisz, 2016). The first stage of the research was summarised in Okruszko (1960), which can be treated as a description of the general theory of the mursh-forming process. Other papers have addressed the problem of changes in water properties (e.g. Szuniewicz and Szymanowski, 1977; Okruszko, 1979; Szuniewicz, 1979; Gawlik, 1992; Piaścik and Łachacz, 1997), humic substances (e.g. Okruszko and Kozakiewicz, 1973; Walczyna, 1974; Sapek A. and Sapek B., 1986; Sapek, B. and Sapek, A., 1987, 1993; Wójciak, 2004), the transformations of iron (Fe), calcium (Ca) and aluminium (Al) compounds (Piaścik, 1977), as well as phosphorus (P) (Okruszko, 1964; Przesmycka, 1974; Ziółek, 2007; Becher et al., 2018, 2020; Debicka et al., 2021). Scientists have attempted to explain the phenomena related to the process of transformation of peat into mursh (the formation of a characteristic grainy or granular structure) using micromorphological methods (Kowaliński, 1964; Drozd et al., 1987; Róg, 1991). Analyses of the elements potentially available to plants were also improved during this time (Okruszko and Walczyna, 1970; Sapek A. and Sapek, B., 1992, 1997).

Research showed that drainage and agricultural use of organic soils leads to their degradation (Okruszko, 1956, 1993; Marcinek, 1976; Marcinek and Spychalski, 1998; Piaścik and Łachacz, 2001; Okruszko and Ilnicki, 2003; Ilnicki and Zeitz, 2003). The mineralisation of soil organic matter resulted in a loss of organic matter and a decrease in the thickness of the organic horizon (Jurczuk, 2011; Glina et al. 2016c; Oleszczuk et al. 2022), i.e. peatland subsidence, and consequently, the soils were transformed from organic soils to mineral soils, referred to in the literature as the "disappearance of peatlands" (Rząsa, 1963; Lipka, 1978; Lipka et al., 2017; Łachacz, 2001; Łachacz et al., 2023).

Since the 1990s, Polish soil science has been dominated by the idea that rational use and protection of organic soils is of critical importance. Scientific research conducted over many years has provided substantial data on the distribution and properties of these soils, both at the national (Żurek, 1987; Ilnicki and Żurek, 1996; Dembek et al., 2000; Lipka, 2000; Ilnicki, 2002; Kotowski et al., 2017) and regional levels (e.g. Zawadzki, 1957; Rząsa, 1963; Mocek, 1978; Borowiec, 1990; Tobolski et al., 1997; Urban, 2004; Becher, 2013). Attention was also paid to those organic soils that cover a relatively small area of the country and yet constitute a natural phenomenon or interesting landscape element, such as organic carbonate soils (Zawadzki, 1957), lacustrine carbonate soils (Uggla, 1976; Meller, 2006; Lemkowska and Sowiński, 2018; Jarnuszewski et al., 2023), gyttja soils (Uggla, 1968; Mendyk et al., 2016; Markiewicz et al., 2017; Kruczkowska et al., 2021; Łachacz and Nitkiewicz, 2021) and organic soils in the mountains (Skiba and Komornicki, 1983; Bogacz, 2005; Malawska et al., 2006; Skiba et al., 2011; Kabała et al., 2013; Drewnik et al., 2018; Nicia et al., 2018).

The primary studies on Polish folisols were conducted by Skiba (2006), Skiba et al. (1998, 2011, 2014), Drewnik et al. (2015), Kacprzak et al. (2006), Musielok et al. (2013), Kabała et al. (2013) and Telega (2022). Many of these authors found that climate, geomorphological conditions and plant communities can cause acidic epihumus (Oh) layers to form on any rock substrate (Kacprzak et al., 2006; Skiba, 2006). These studies were mostly focused in the Tatra Mountains, the Eastern Carpathians (Skiba et al., 1998, 2014) and the Sudetes (Skiba at al., 2011; Musielok et al., 2013; Kabała et al., 2013; Telega, 2022). Folisols have also been found on granite, sandstone, Carpathian flysch, rhyolites and limestone. The ecological and hydrological role of folisols in the natural environment has been emphasised (Kacprzak et al., 2006).

The use of new research methods significantly expanded the state of knowledge with regard to the processes that occur in organic soils (Łachacz et al., 2009; Oleszczuk et al., 2009; Gnatowski et al., 2010, 2022; Kalisz et al., 2010, 2015; Hewelke et al., 2016; Papierowska et al., 2018; Glina et al., 2019; Glina et al., 2021; Becher et al., 2022, 2023; Mencel et al., 2022; Kalisz and Łachacz, 2023). Currently, in Poland, as in other countries, considerable attention has been paid to the environmental role and functions of organic soils.

3. Crucial properties and functions of organic soils

Although peat soils cover a relatively small area, with peat accumulation rates of 0.5–1.0 mm yr^{-1} (Renou-Wilson et al., 2019), they are crucial for organic C sequestration, water quality and retention, immobilisation of various compounds, the maintenance of biodiversity, and as habitats for various fauna and flora species (Joosten and Clarke, 2002). In addition, peatlands provide many ecosystem services, such as agricultural biomass production, a growing media for horticultural production, a fuel source for energy, as well as places for recreation and art (Kimmel and Mander, 2010). Peat soils are also so-called ecotone zones i.e. transitional sites between land and water ecosystems. They act as "the kidneys of the landscape" due to their ability to retain and bind various chemical compounds. Organic soils play a buffering role for excess nutrients that endanger surface and ground water quality, as well as adjacent soils.

Natural water-saturated peatlands sequester CO_2 from the atmosphere (in peat vegetation) and emit methane (CH_4) (Maljanen et al., 2010), and thus play an important role in the regulation of the global climate. The global peatland C stock is estimated at approximately 650 Gt, of which 85% is stored in northern hemisphere peatlands (Xu et al., 2018; Hugelius et al., 2020; Harris et al., 2022). The C stock in peatlands has been estimated to be equivalent to one-third of global soil organic C (Page and Baird, 2016). Drainage and use of peat soils increase soil aeration and transform peatlands from CO_2 sequesters into net emitters (although CH_4 emissions may decrease) (Maljanen et al., 2010; Frolking et al., 2011; Kasimir et al., 2018; Tuohy et al., 2023). Disturbance to peatlands from climate change and human activity affects their C storage potential. This leads to the loss of a significant part of their C stock as dissolved organic carbon (DOC) via fluvial pathways (Glina et al., 2022). Although the labile organic fraction constitutes a small proportion of soil organic matter (SOM), it is one of the most mobile and bioavailable forms (Ghani et al., 2013; Kalisz et al., 2015; Cao et al., 2017; Norberg et al., 2018) and can be indicative of the processes that control SOM accumulation and stabilisation (Glina et al., 2016a; Bojko et al., 2017; Kalisz et al., 2021). Organic matter is an important soil constituent that provides a variety of functions that influence plant growth, greenhouse gases (GHGs) emissions, and the physical and chemical properties of the soil (Smólczyński and Orzechowski, 2010a; Heller and Zeitz, 2012; Lehmann and Kleber, 2015; Kalisz and Łachacz, 2023).

Natural peatlands are water "reservoirs" that can mitigate spring flooding and can remain resilient even during periods of drought. Organic soils retain water in the landscape and the outflow is well distributed over time, which is especially important in river valleys (organic soils can mitigate floods). During drought periods, organic soils release water to the rivers and surrounding lands. The ability to retain water derives from an inherent low bulk density, as well as high total porosity and distribution of pore size classes (Szatyłowicz et al., 2007; Gnatowski et al., 2010; Hewelke et al., 2016), which also depend on the type of peat, degree of decomposition, degree of humification, drainage and transformation by mursh-forming process, as well as topsoil siltation (Smolczynski et al., 2021). The relationship between soil properties and water retention and conductivity have been well-described by pedotransfer functions (Gnatowski et al., 2010; Szatyłowicz et al., 2007). In drained peat soils, the water retention function is diminished and the physical properties are changed. The topsoil of mursh is characterised by a small volume of macropores (range: 6% to 18%), and the average content of air pores is approximately 10% (Orzechowski et al., 2022; Smólczyński et al., 2016). Silted mursh organic soils are characterised by a smaller volume of macropores and a larger volume of micropores (leads to reduced volume of mesopores and consequently water availability to plants), which accounts for more than half of their total porosity. Some drained organic soils that are still able to maintain an ability to retain water may change their volume, which results in swelling and shrinking processes (when the water table fluctuates widely) (Oleszczuk et al., 2009). The diminished water retention abilities in organic soils are a consequence of increasing hydrophobicity in the drained topsoil (Łachacz et al., 2009; Kalisz et al., 2015; Papierowska et al., 2018; Szatyłowicz et al., 2024). Silted mursh materials are frequently moderate or strongly hydrophobic, whereas peats that are not silted are very strongly or extremely hydrophobic. The hydrophobicity is related to the organic matter content, degree of humification, and the degree of organic soil siltation. In general, hydrophobicity occurs in soils that contain more than 20% organic matter, although colluvial or alluvial admixtures in the organic mass may diminish its concentration (Orzechowski et al., 2013; Kalisz et al., 2015).

Disturbance of water properties in organic soils also leads to the disturbance of N compounds. Mineralisation of organic matter releases inorganic N to the mursh (Tiemeyer et al., 2007), and thus increases the availability of N to the plants (Pauli et al., 2002). Mineralisation of nitrogenous compounds occurs both during the growing season and, more critically, outside of the growing season when it endangers groundwater quality. The amount of N released during the non-growing season in mursh soils has been shown to range from 5 to 9 mg·dm^{-3}. A mitigating factor of N mineralisation is peatland siltation. Research carried out by Smólczyński and Orzechowski (2010b) showed that smaller amounts of mineral N were found in peat layers under colluvial sediments than in mursh materials, which is particularly important for alder peats as they are most vulnerable to these processes.

Organic soils contain variable amounts of P. For example, fen peats contain approximately 0.5 g P kg^{-1}, whereas mursh materials contain 1.0 to 2.4 g P kg^{-1} (Łachacz et al., 2023). The increase in P content after drainage, due to mursh formation, may lead to P dispersion, entailing the process of eutrophication (Meissner et al., 2008; Becher et al., 2020). Moreover, the high variability in redox conditions in both wet and drained peat soils has a significant effect on the forms and solubility of P (Becher at al., 2018). Moreover, P release as a result of drying and rewetting of organic soils may limit the ability of natural, restored and constructed wetlands and streams to provide substantial ecosystem services. Along landscape flow paths, the released soil P may cause aquatic or semi-aquatic ecosystems to act as P sources rather than sinks, potentially contributing to harmful eutrophication in vulnerable downstream ecosystems (Kinsman-Costello at al., 2016). Peatlands may release P to adjacent ecosystems and become nutrient-poor systems for an unknown period. From an ecological restoration and target species point of view, the high availability of nutrients in highly decomposed peat soils is very important (Zak et al., 2014).

Riet Van de et al. (2013) reported that constant flooding of meadows on drained organic soils leads to the release of large amounts of compounds, especially P, into the groundwater, much more than in the case of mineral soils, driven by the higher content of Fe-bound P in peat formations. In turn, the release of P from organic soils is dependent on geochemical conditions. In organic soils that contain large amounts of Ca but are low in Fe, insoluble forms of Ca phosphates are formed, which in turn may limit the availability of P after drainage (Forsmann and Kjaergaard, 2014).

The content of other macro- and micro-elements in organic soils is also dependent on water conditions (Bieniek, 1988). Another factor that influences their concentration is the location of the soil in the landscape. Organic soils located at the edge of moraine inland depressions have been shown to have the highest concentration of macro- and micro-elements, especially magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn), and lower located mursh soils – Ca, P and sodium (Na). The concentrations of Fe, Mn and P have been shown to be related to the fluctuations of groundwater and the redox potential (Smólczynski et al., 2015). These soils are the first barrier to the biogens that may infiltrate nearby ecosystems and groundwaters (Sowiński et al., 2004; Sowiński, 2016; Sowiński et al., 2016).

The properties of folisols are related to the content and quality of the organic matter accumulated in the topsoil layer. *Folik* horizons are usually strongly acidic (pH_{H2O} 3.1–4.1) (Drewnik et al., 2015), (pH_{H2O} 3.6–4.8) (Skiba et al., 2011), (pH_{H2O} 3.6–4.3) (Musielok et al., 2013). Even folisols developed on calcareous bedrock are acidic at pH_{H2O} 5.8 (Kacprzak et al., 2006). Base saturation is usually low at 10–35% (Telega, 2022), only rarely exceeding 50% (Kabała et al., 2013). Nitrogen content ranges from 0.9 to 1.8%, with C:N ratios between 26 and 32 (Drewnik et al., 2015).

The vegetation that grows on organic soils frequently consists of rare and endangered species, so these ecosystems are very unique and important (Hedberg et al., 2014). Also, in many instances, these ecosystems are the only "shelter" or "refugium" for specific species (both fauna and flora) in the landscape (Sender et al., 2022). Moreover, organic soils with ongoing peat formation are the archives of environmental changes and if they remain undisturbed, may store critical information on historical climate change, vegetation cover and human activity (Słowiński et al., 2016; Dobrowolski et al., 2019; Kruczkowska et al., 2020; Mirosław-Grabowska et al., 2020; Magiera et al., 2021; Okupny and Pawłowski, 2021; Petera-Zganiacz et al., 2022).

4. Classification of organic soils in Poland

The specific properties of organic soils described above (of which the most important are the high organic C content, and low bulk density and high porosity values) distinguish them from mineral soils. In SGP 6 (2019), organic soils are defined as organic materials (*containing 12% organic C if saturated with water for ≥30 consecutive days in most years, or containing ≥20% organic C if saturated with water for <30 days*) either: a) starting ≥ 30 cm from the soil surface and having within ≥60 cm from the soil surface combined thickness of ≥30 cm; or b) starting at the soil surface and with a thickness of ≥10 cm, directly overlying continuous rock or coarse fragments the interstices of which are filled with organic material to a depth of ≥30 cm from the soil surface. Therefore, the current approach to the classification of organic soils is based on specific quantitative parameters (Table 1). However, both SGP 1 (1956) and SGP 2 (1959) reflected the complexity and diversity of environmental conditions and soil genesis. In sections 4 and 5 of this review paper, the Polish and English soil units used in successive

Table 1
General characteristics of soil materials (excluding litter materials) forming organic soils according to SGP 6 (2019)

Specification	Peat			Gyttja			Mud		Mursh
	fibric	hemic	sapric	organic	calcareous	meadow limestone (marl/chalk)	lacustrine	telmatic	
$C_{org.}$ (%)	≥12	≥12	≥12	≥12	≥12	<12	≥12	12–25	≥12
$CaCO_3$ (%)	*	*	*	<20	≥20	≥20	*	*	*
Degree of decomposition (%) von Post	<33 H1–H3	33–66 H4–H6	>66 H7–H10	–	–	–	>66 H7–H10	>66 H7–H10	–**
Elasticity	–***	–***	–	+	(+)	–	–	–	–
Coprolites	–	–	(+)	+	+	–	–	–	–
Addition of clastic material	small	small	various up to more than 70%	very small	small	small	various up to more than 70%	various up to more than 70%	various up to more than 70%
Colour (general)	yellow to brown	different shades of brown	brown to black	greenish, generally light	whitish, generally light	whitish, generally light	blackish	blackish	different shades of brown to black

Explanations: – – absent; + – present; (+) – present in smaller extend or only in some kinds of materials; * – some kinds of peats as well as mud and mursh materials have substantial addition of calcium carbonate (therefore are termed calcareous); ** – mursh by definition is strongly decomposed (sapric), however this feature is not determined by von Post method caused by normally dry/fresh conditions in the field; *** – some kinds of peats, especially fibric and hemic ones display specific elasticity caused by the presence of plant fibres. However, this elasticity differs from that displayed by organic and some calcareous gyttja materials versions of SGP are cited in the form they were written. In the described soil classifications, organic soils were associated with the hydromorphic soil type (in Polish: *gleby bagienne*), with the following soil subtypes distinguished: Gley soils (in Polish: *gleby glejowe zabagniane*), peat soils (in Polish: *gleby torfowe*) and murshic soils (in Polish: *gleby murszowe*). While only peat soils and murshic soils would probably meet the current criteria for organic soils, this is difficult to assess because both the early classification schemes (SGP 1 and SGP 2) did not clearly present defined quantitative criteria, especially in relation to the organic C content and the minimum thickness of organic materials. Within the peat subtypes, the following soil units were distinguished: Peat soils developed from fen peatlands (in Polish: *gleby torfowe wytworzone z torfów torfowisk niskich*), peat soils developed from transitional peatlands (in Polish: *gleby torfowe wytworzone z torfów torfowisk przejściowych*) and peat soils developed from raised peatlands (in Polish: *gleby torfowe wytworzone z torfów torfowisk wysokich*).

In SGP 3 (1974), hydromorphic soils were moved to a higher classification unit – *class*. Within this unit, two soil types were distinguished: Peat soils and mud soils (in Polish: *gleby mułowe*). The latter were described as soils that contain a significant organic matter proportion that was mostly well humified. A separate group, the so-called lake gyttja (in Polish: *gytja jeziorna*), was distinguished among the muds of limnetic origin.

In regard to the classification of peat soils, a minimum thickness of peat material (25 cm) was also introduced. Moreover, characteristic peat-forming plant species and soil pH values were provided for the individual soil subtypes. The 3rd edition (SGP 3) also introduced a new class of post-hydromorphic soils (in Polish: *gleby pobagienne*): Murshic soils and black earths (in Polish: *czarne ziemie*). Of the soils described above, only murshic soils, which form as a result of the mursh-forming process (the process of physical and chemical transformation of organic materials that occurs after their dehydration) of peat or mud materials, could be considered as organic soils.

The 4th edition (SGP 4, 1989) was similar to the previous versions and was based on environmental (qualitative) criteria. However, for the first time, diagnostic horizons were introduced, including *histic*, which consisted of organic material, such as "peat, mud, gyttja or organic mursh", which contained at least 20% organic matter (at least 12% organic C content) and no clay, or at least 30% organic matter (18% organic C content) when the clay content was > 50% . When the thickness of this horizon was > 30 cm, the soil was classified as an organic soil. These soils were merged in a division (in Polish: *dział*) of hydrogenic soils (in Polish: *gleby hydrogeniczne*). *Peat soils* and *mud soils* were assigned to the order (in Polish: *rząd*) *bog soils* (in Polish: *gleby bagienne*), while murshic soils were assigned as a separate soil type to the order *post-bog soils* (in Polish: *gleby pobagienne*). In SGP 4, a new type of organic soil was introduced – earth-covered murshic soils (in Polish: *gleby namurszowe*); soils where the surface layer (10–30 cm in thickness) was composed of mineral or mineral-organic materials of alluvial, colluvial or anthropogenic origin, which directly overlay peat or mursh materials. It should be noted that the general description of organic soil types and subtypes in this edition was very detailed, including examples of soil profile morphology, the typical development conditions and some specific soil parameters (i.e. pH and soil structure).

In SGP 5 (2011), several important changes were introduced to the classification of organic soils. The previously derived criteria were replaced with those adopted from the WRB classification (IUSS Working Group WRB, 2006) and NRCS Soil Taxonomy (1999). Now, the classification of organic soils was based not on the general soil formation processes of organic materials and their transformation after drainage, but instead on their properties, i.e. morphology of the soil profile, the degree of peat decomposition and presence of mineral, gyttja or mud layers in the control section of soil profile to a depth of 130 cm. Moreover, the diagnostic soil materials (sapric, hemic, fibric, limnic) and a list of diagnostic organic soil horizons were supplemented by folic and murshic.

According to SGP 5 (2011), organic material should fulfil the following criteria: 1) *contain at least 12–18% organic C (dependent on the clay content) if saturated with water for ≥ 30 consecutive days in most years, or artificially drained; 2) contain ≥ 20% organic C if saturated with water for <30 consecutive days in most years.* A completely new approach included the introduction of a control profile of organic soils with a thickness of 130 cm, which was divided into three sections: an upper section (0–40 cm), a middle section (40–100 cm) and a lower section (100–130 cm) was introduced. The middle section equated to the main soil layer because its nature and properties determined the soil type and subtype. The soil material in the upper and middle sections formed the basis to distinguish soil types and subtypes, while the middle and lower sections were used to distinguish the soil subtypes only. Organic soils were composed of organic materials of ≥ 40 cm thickness, and the only exception was when organic materials lay directly on solid rock or rock fragments (then the minimum thickness was set at 10 cm). In the order *organic soils*, the following soil types were distinguished: fibric peat soils (in Polish: *gleby torfowe fibrowe*), hemic peat soils (in Polish: *gleby torfowe hemowe*), sapric peat soils (in Polish: *gleby torfowe saprowe*), organic folisols (in Polish: *gleby organiczne ściółkowe*), limnic organic soils (in Polish: *gleby organiczne limnowe*) and murshic soils. The peat soil types denoted the degree of peat decomposition that prevailed in the soil profile – fibric peat (slightly decomposed peat), hemic peat (moderately decomposed peat) and sapric peat (strongly decomposed peat). This was a significant change compared to previous soil classifications, which were based on the ecological type of the peatland.

The current edition of Polish Soil Classification (SGP 6, 2019) continued the important decision to correlate the requirements for diagnostic horizons and materials with the WRB classification (IUSS Working Group WRB, 2015). The general classification criteria for organic soils were described at the beginning of this section. Organic soils (as defined in SGP 5) were merged as a separate order (soils developed from organic material with a histik/murszik/folik horizon of ≥ 30 cm or 10 cm thickness), within which the following four types were distinguished: Murshic soils, peat soils, limnic soils and folisols.

Detailed classification criteria of the organic soil types and the numerous respective subtypes with their most common WRB equivalents are presented in the next section.

5. Types of organic soils in Polish Soil Classification (SGP 6, 2019)

5.1. Peat soils

In Poland, peat soils (in Polish: *gleby torfowe*) can be considered as the most important soil type among organic soils, given their land cover, their ongoing accumulation of organic matter, and the large stocks of organic C sequestered within. They consist mainly of indigenous plant remnants that have accumulated *in situ*. SOM starts to accumulate when microbial decomposition of plant matter is halted or slowed down due to limited oxygen availability in water-saturated sites. Organic soils have a positive organic matter balance in natural conditions (i.e. not subjected to artificial drainage). Peat soil contains both plant detritus (with preserved tissue structure) and humic substances, the latter generated by the decomposition of the former. Depending on the ratio between the main components, peat materials can be classified as fibric, hemic or sapric. The 'degree of peat decomposition' (humification) is a metric that describes the proportion of amorphous humus in relation to the total peat mass. The decomposition of plant debris during its accumulation (primary decomposition) should be distinguished from the secondary decomposition that occurs after the peat has been drained (the mursh-forming process). Humification affects the diameter and geometry of soil pores and is thus a major determinant of soil physical properties (such as water holding capacity and permeability). In a sense, the measure of peat decomposition corresponds to grain size distribution in mineral soils. The presence of plant tissues shapes the rheological properties and bearing capacity of peat soils. Another determinant of peat soil parameters is the presence of allochthonous mineral soil material (i.e. the degree of siltation).

Organic soils can be found in various physiographic positions, which influence the water supply. Peat soils usually occur in depression landforms (basins), with water from neighbouring areas flowing in and pooling within, but they can also be found on plains with limited groundwater outflow. Peatlands occur in the depressions that are typical of young-glacial landscapes, in river valleys (common for old-glacial landscapes), and on the slopes of foothills. Spring-fed fens are a unique case in that they are supplied with surfacing groundwater. With a large inflow of pressure-ejected (artesian) water, spring-fed fens can have a convex (dome fens) or hanging (slope fens) shape. Some raised bogs (mountain or coastal, Atlantic type) can also produce convex landforms.

Traditionally, peatlands have been divided into fens, transitional and raised bogs, according to the water source, nutrient status and morphology of the peat deposit (Kulczyński, 1949). More detailed classifications based on the geobotanical features of the peat, namely the subfossil peat-forming plant communities, were elaborated by Tołpa et al. (1967). In SGP 6 (2019), a new non-hierarchical unit of soil classification was introduced, namely variety. Based on the dominant peat in the upper layer (0–50 cm), the following varieties of peat soils were distinguished: raised, transitional and fen peatlands, which were further subdivided into low-moss peats, sedge peats, reed peats and alder forest peats. The water-supply classification used water origin, chemical composition, oxygenation and mobility in the landscape to disaggregate organic soils as ombrogenic, soligenic, fluviogenic, basin and hanging soils. Peat soils, such as soligenic-fluviogenic, are often fed by mixed water sources.

With the exception of the murshic peat soil subtype, peat soils are overgrown with peat-forming vegetation. The groundwater level is close to the surface all year round, or at least for 30 consecutive days, which ensures that the soil is fully water-saturated and drives the peat-forming process. The large proportion of water-filled pores (70–95% vol.) and the organic soil mass (plant fibres) ensure that the surface of peat soil act like a sponge, which can deform under the weight of a person, and the resultant footprint immediately fills with water. Drainage of peat soils results in the development of a > 30 cm thick murszik horizon, thus prompting the transition of these soils to the murshic type.

In SGP 6 (2019), seven sub-types are defined based on the diagnostic materials and layers present in the soil profile, and the thickness of the layers:

a) Earth-covered peat soils (in Polish: *gleby natorfowe*).
The organic soil is covered with a layer of mineral sediment of at least 10 cm thick. The sediment may be of colluvial, fluvial, aeolian and slope (in mountainous areas) origin. In some cases, this mineral material is deliberately deposited as an amelioration practice. The underlying layer is made up of fibric, hemic or sapric peat. Earth-covered peat soils usually form narrow transition zones (ecotones) on the borders of peatlands. The surface mineral sediment partially shields the underlying peat from the air and slows down decomposition.

b) Fibric peat soils (Fig. 1b) (in Polish: *gleby torfowe fibrowe*).
Fibric peat dominates the peat layer to a depth of 100 cm (or comprises the entire profile if it does not reach a depth of 100 cm). The underlying layer can be hemic, sapric or mineral. These soils can often be found in natural (undrained) habitats.

c) Hemic peat soils (Fig. 1a) (in Polish: *gleby torfowe hemowe*).
Hemic peat dominates the peat layer to a depth of 100 cm (or comprises the entire profile if it does not reach a depth of 100 cm). In Poland, hemic peat soils cover large complexes of lacustrine fens, lakeside peatlands and valley peatlands.

d) Sapric peat soils (in Polish: *gleby torfowe saprowe*).
Sapric peat dominates the peat layer to a depth of 100 cm (or comprises the entire profile if it does not reach a depth of 100 cm). It often forms shallow peat soil profiles.

e) Murshic peat soils (in Polish: *gleby torfowe murszowe*).
The surface layer of the profile contains a murszik horizon of < 30 cm, which is indicative that the mursh-forming process is at an early stage. Deeper fibric, hemic or sapric peats occur and comprise the entire profile or are underlain by mineral formations.

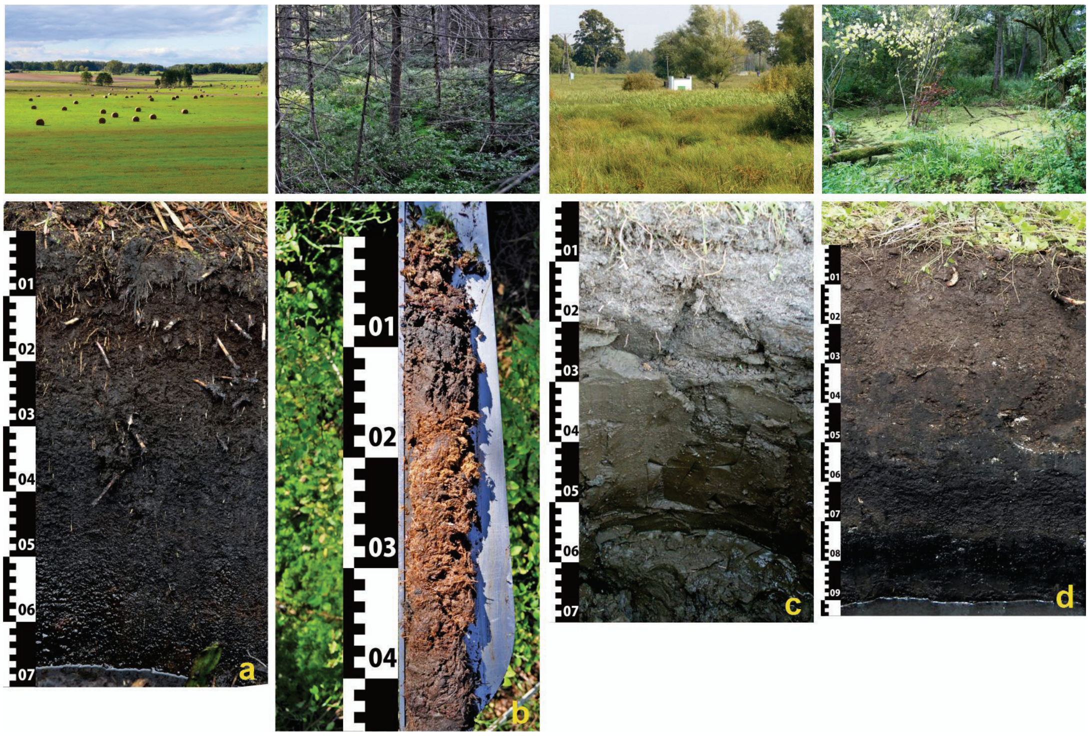

Fig. 1. Organic soils of Poland: (a) hemic peat soil (SGP: gleba torfowa hemowa) – WRB: Drainic Hemic Histosol – Olsztyn Lakeland; (b) fibric peat soil (SGP: gleba torfowa fibrowa) – WRB: Drainic Hemic Histosol – Stołowe Mountains; (c) gyttja soil (SGP: gleba gytiowa) – WRB: Sapric Histosol (Limnic) – Mrągowo Lakeland; (d) muddy soil (SGP: gleba mułowa) – WRB: Sapric Histosol (Limnic) – Chełmno Lakeland. Abbreviations: SGP – Polish Soil Classification (Systematyka gleb Polski, 2019), WRB – World Reference Base for Soil Resources (IUSS Working Group WRB, 2022)

f) Gyttja peat soils (in Polish: *gleby torfowe gytiowe*).
Layer (layers) of gyttja with a combined thickness of at least 30 cm is (are) present to a depth of 100 cm in a soil profile that is composed of fibric, hemic or sapric peat. These soils occur in eutrophic lakes where peat-forming plants have entered the final stage of terrestrialisation, often in the form of a floating mat. Some fibric gyttja peat soils meet the criteria of the *floatic* principal qualifier under WRB (2022).

g) Muddy peat soils (in Polish: *gleby torfowe mułowe*).
A layer (or layers) of mud with a combined thickness of at least 30 cm is (are) present to a depth of 100 cm in a soil profile composed of peat. Soils of this type are found in the valleys of larger rivers with a well-preserved natural water regime.

In general, peat soils according to SGP 6 (2019) belong to the Histosol soil reference group in the WRB classification (IUSS Working Group WRB, 2022), and the order *Histosols* in the Soil Taxonomy scheme (Soil Survey Staff, 2022), although shallow peat soils (from 30 to < 40 cm of peat material) might be classified as Histic Gleysols and Humaquepts.

5.2. Limnic soils

Soils developed from the organic materials deposited in water environments were recognised for the first time in SGP 3 (1974). As described in section 4, these soils, called mud soils (in Polish: *gleby mułowe*), were distinguished as one of two types: together with peat soils (in Polish: *gleby torfowe*) and within the class *bog soils* (in Polish: *gleby bagienne*). The mud soil type (in Polish: *gleby mułowe*) included three subtypes: proper mud soils (in Polish: *gleby mułowe właściwe*), mud-gyttja soils (in Polish: *gleby mułowo-gytiowe*) and peat-mud soils (in Polish: *gleby torfowo-mułowe*). Since SGP 3, these soils have been recognised by Polish soil scientists with some changes in their systematic position.

In SGP 4 (1989), new hierarchical units were introduced into the classification. Mud soil type was now present within the order *bog soils* (in Polish: *gleby bagienne*), becoming part of the hydrogenic soil division. As with the previous edition, three subtypes were distinguished: proper mud soils (in Polish: *gleby mułowe właściwe*), peat-mud soils (in Polish: *gleby torfowo-mułowe*) and gyttja soils (in Polish: *gleby gytiowe*), depending on the character of the organic material.

SGP 5 (2011) brought about substantial changes as it was more correlated to the WRB and Soil Taxonomy schemes (see section 4). In regard to soils developed from various organic sediments accumulated under water, diagnostic organic *limnic materials* were listed, which included gyttja, diatomaceous earth, lacustrine marl, lacustrine chalk and muds. Nevertheless, strict, unambiguous criteria were not presented, which resulted in some problems with the correct identification of these materials, for example, a type of limnic soils (in Polish: *gleby limnowe*) was placed within the order *organic soils*. Once again, three subtypes of limnic soils were presented. However, different (in comparison to previous SGP editions) features were taken into account when their affiliation was determined and this was reflected in their nomenclature: typical limnic soils, hemi-limnic soils and calcareous limnic soils (in Polish: *gleba limnowa typowa, gleba hemowo-limnowa* and *gleba węglanowo-limnowa,* respectively) (Świtoniak et al., 2016).

In SGP 6 (2019), a list of well-defined diagnostic horizons with limnic materials was presented, which referred to the traditional national division of such sediments, as well as to the findings of researchers who had examined specific soils that developed from these materials (e.g. Kalisz and Łachacz, 2009; Długosz et al., 2018; Łachacz and Nitkiewicz, 2021; Łachacz et al., 2023)., Five subtypes were recognised within limnic soils:

a) Gyttja soils (Fig. 1c) (in Polish: *gleby gytiowe*).
Gyttja is the dominant component of the soil organic material.
b) Muddy soils (Fig. 1d) (in Polish: *gleby mułowe*).
Organic mud is the dominant component of the soil organic material.
c) Subaquatic limnic soils (in Polish: *gleby limnowe podwodne).*
The soil surface is permanently covered with 10–150 cm of water (outside periods of flooding and drought).
d) Peaty limnic soils (in Polish: *gleby limnowe torfowe*).
A layer (or layers/interlayers) of peat with a combined thickness of at least 30 cm is (are) present to a depth of 100 cm.
e) Murshic limnic soils (in Polish: *gleby limnowe murszowe*).
A murszik diagnostic horizon of < 30 cm thick is present.

In practice, as both gyttja soil and muddy soil subtypes are "principal" subtypes (Kabała et al., 2019), the name "limnowa" is replaced with one of them, e.g. the soil developed from organic mud with a 20 cm thick murshik horizon would then be called murshic muddy soil (in Polish: *gleba mułowa murszowa*).

The nearest equivalents to gleby limnowe in the WRB classification (IUSS Working Group WRB, 2022) are Sapric Histosols (Limnic) for gyttja soils, Sapric Histosols (Fluvic/Limnic) for muddy soils, Subaquatic Histosols (Limnic) for subaquatic limnic soils Histosols (Limnic) for peaty limnic soils and Murshic Histosols (Limnic) for murshic limnic soils. In regard to the Soil Taxonomy classification (Soil Survey Staff, 2022), these equivalents are Sapric/Typic Haplowassists for the subaquatic limnic soils and Limnic Haplosapristrs/Haplohemists for the remainder of the subtypes defined within SGP. Due to the different soil organic C threshold contents for organic material employed in SGP (compared to WRB and Soil Taxonomy), Polish organic limnic soils are commonly classified as Gleysols (Limnic), often with humic (hyperhumic) or mulmic qualifiers, and as Histic/Typic Humaquepts, respectively.

5.3. Murshic soils

The murshic soils (in Polish: *gleby murszowe*) in SGP 1 (1956) and SGP 2 (1959) were described as a subtype within the post-hydromorphic soil type (in Polish: *gleby pobagienne*). However, since SGP 3 (1974) and up to SGP 6 (2019), these soils have been described as a separate type. Murshic soils have developed from organic materials (peat, gyttja, mud) because of their permanent artificial or natural drainage systems and from pedogenic transformation. As a result of these processes, a surface (diagnostic) murszik horizon is formed, with a minimum thickness of 30 cm. The murszik horizon consists of organic materials that are characterised by the presence of a pedogenic structure (grainy or granular in most cases), and increased organic matter humification compared to the parent organic material (peat or limnic materials). When drained for long periods, vertical cracks may appear within the profile. Periodic drying and the inherent characteristics of the murszik material mainly determine the functional properties of murshic soils and distinguish them from other organic soils. The morphology and properties of organic materials that occur in the soil profile under the mursh layer are the main criteria used to distinguish the murshic soil subtypes. In SGP 6 (2019), the following murshic soil subtypes are included:

a) Earth-covered murshic soils (in Polish: *gleby namurszowe*).
The murszik horizon is covered with mineral material of ≥10 cm thickness.
b) Fibric murshic soils (in Polish: *gleby murszowe fibrowe*).
Slightly decomposed peat dominates, and underlies the murszik horizon to a depth of 100 cm (or the entire layer of underlying peat if it does not reach a depth of 100 cm).
c) Hemic murshic soils (Fig. 2b) (in Polish: *gleby murszowe hemowe*).
Moderately decomposed peat dominates, and underlies the murszik horizon to a depth of 100 cm (or the entire layer of underlying peat if it does not reach a depth of 100 cm).
d) Sapric murshic soils (in Polish: *gleby murszowe saprowe*).
Strongly decomposed peat dominates, and underlies the murszik horizon to a depth of 100 cm (or the entire layer of underlying peat if it does not reach a depth of 100 cm).
e) Gyttja murshic soils (in Polish: *gleby murszowe gytiowe*).
A layer or layers of gyttja with a total thickness of ≥ 30 cm to a depth of 100 cm.
f) Muddy murshic soils (in Polish: *gleby murszowe mułowe*).
A layer or layers of mud with a total thickness of ≥ 30 cm to a depth of 100 cm.
g) Thin murshic soils (Fig. 2a) (in Polish: *gleby murszowe płytkie*).
The total thickness of organic materials is ≤ 50 cm.

The most important equivalents of murshic soils in the WRB classification (IUSS Working Group WRB, 2022) are Murshic Histosols (if the thickness of the organic layer is at least 40 cm) or Histic Gleysols (Drainic) (if the thickness of the organic layer is < 40 cm). When the murshic material contains 8–20% organic C and might fulfil the criteria for mulmic material, then a mulmic supplementary qualifier may be added to Histosols or Gleysols. In the Soil Taxonomy classification (Soil Survey Staff, 2022), the most common equivalent of murshic soils are Histosols and Histic Humaquepts.

5.4. Folisols

In SGP 6 (2019), folisols (in Polish: *gleby ściółkowe*) are listed within the order *organic soils*. Folisoils are composed

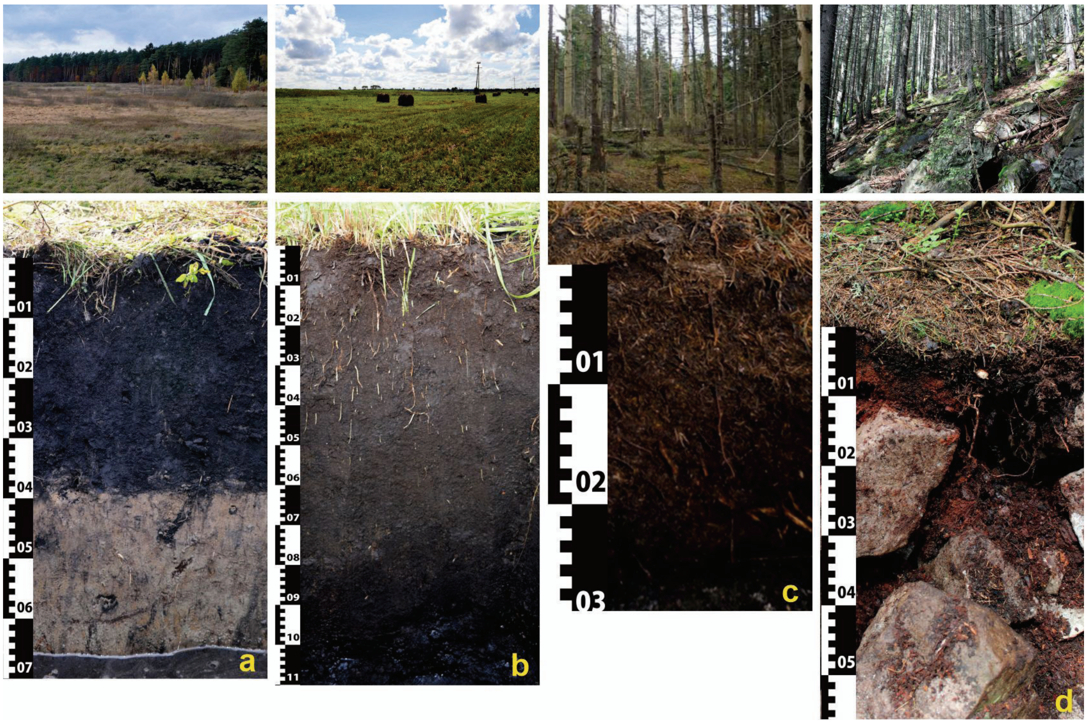

Fig. 2. Organic soils of Poland: (a) thin murshic soil (SGP: gleba murszowa płytka) – WRB: Eutric Histic Gleysol – Brodnica Lakeland; (b) hemic murshic soil (SGP: gleba murszowa hemowa) – WRB: Murshic Hemic Histosol – Middle Noteć River Valley; (c) rocky folisol (SGP: gleba ściółkowa skalista) – WRB: Folic Rockic Histosol – Stołowe Mountains; (d) debris folisol (SGP: gleba ściółkowa rumoszowa) – WRB: Folic Mawic Histosol – Western Tatra Mountains. Abbreviations: as in Fig. 1

of organic material derived from litter (leaves, wood fragments, bark, seeds and animal detritus) at least 10 cm thick when lying directly on solid rock, or at least 30 cm thick when lying on weathered rocks or in the spaces between rock fragments. Folisols have a folik horizon with > 20% organic C that has accumulated under oxygen-rich conditions. The litter material is saturated with water for < 30 days. Folisols encompass four subtypes:

a) Typical folisols (in Polish: *gleby ściółkowe typowe*) with an organic layer at least 30 cm thick that covers the mineral horizon, not overlying solid rock or coarse-skeletal material.
b) Rocky folisols (Fig. 2c) (in Polish: *gleby ściółkowe skaliste*) with an organic layer at least 10 cm thick overlying solid carbonate-free rock.
c) Debris folisols (Fig. 2d) (in Polish: *gleby ściółkowe rumoszowe*) with an organic layer at least 30 cm thick within carbonate-free coarse-skeletal material that fills the spaces between rock fragments and on the surface.
d) Calcareous folisols (in Polish: *gleby ściółkowe rędzinowe*), where the organic material covers solid carbonate rock or fills spaces with carbonate coarse-skeletal material.

Folisols originate from transported and accumulated organic material and windthrows (Bochter and Zech, 1985). The resultant deadwood layers serve as an important source of C and nutrients (Maser and Trappe, 1984). Some organic layers can exceed 40 cm in thickness (Skiba et al., 2011; Kabała et al., 2013). In addition, soils that consist of organic matter that fills the empty spaces within slope cover are considered folisols (Kacprzak et al., 2006; Skiba et al., 2011). Here, the slowly decomposing litter is carried by water deep into cracks in the rocks, and accumulates over time (Skiba and Komornicki, 1983; Kacprzak et al., 2006). Organic matter content is one of the most important drivers of plant expansion (encroachment) over coarse-grain parent material (Kabała et al., 2013).

Folisols, which mainly form under specific conditions in cool and humid climates, are vulnerable to fire and erosion. The latter can be intensified, for example, when slopes are stripped of vegetation during logging and road construction, especially on slopes between 20–30° (Nagle, 2000). Climate change may lead to changes in vegetation composition (Suonan et al., 2019) and a slowdown in litter accumulation. Forest stand restoration and the adaptation of forest habitats to the trophic conditions of the soil are also live issues (Gałka et al., 2014). Folisols are mosaic in pattern and co-occur with other soil types and orders. They are strongly morphologically diverse, owing to the geomorphology of the rock-mineral substrate, the type and rate of plant detritus accumulation, the weather, and any disruptions to organic matter deposition. The most important equivalents of folisols in the WRB classification (IUSS Working Group WRB, 2022) are Folic (Rockic/Mawic) Histosols, while folisols are mostly classified as Lithic/Typic Udifolists in the Soil Taxonomy classification (Soil Survey Staff, 2022).

6. Distribution and land use of organic soils in Poland

The distribution and area covered by the soils that are classified as organic in SGP 6 (2019) has not been satisfactorily documented, despite the extensive research conducted in recent decades. On the one hand, this is a consequence of the changed criteria as to what qualifies as an organic soil, but is also the consequence of the very dynamic changes that occur in these soils after drainage. In this context, degradative changes that lead to the loss of organic matter are particularly important, for example, the shift of organic soils with a shallow organic layer to mineral soils.

The first estimates of the area covered by organic soils (then peat soils) in Poland were based on data obtained during the geological documentation of peat deposits, which was mainly carried out in the 1950s, 1960s and 1970s (Żurek, 1987; Ilnicki and Żurek, 1996; Dembek et al., 2000; Ilnicki, 2002). In this inventory, peats were considered to contain over 20% organic matter (referred to as loss-on-ignition) and have an organic layer (peat) of at least 30 cm, which is the same in SGP 6 (2019). As mentioned above, traditionally peatlands were divided into raised, transitional and fens (Kulczyński, 1949; Tołpa et al., 1967). The inventory covered sites with an area of > 1 ha. However, some peatlands, especially in the restricted border zones and within forests used by the army were not included in the inventory. This led to an underestimation of the area of peatlands in Poland. In addition, given the time that has passed since the beginning of the inventory, its usefulness today is significantly limited. Therefore, an update of this inventory was undertaken in the 1990s, which had a broader scope as, in addition to peatlands, it included all wetland areas (peatlands and non-peat wetlands) (Ilnicki, 2002). Based on these updated estimates, it was determined that there were 50,200 peatlands in Poland, which covered 1,322,000 ha, i.e. 4% of the country (Dembek et al., 2000). More recent work by Kotowski et al., (2017), which included the 1990s inventory, forest site type data and some data from soil agricultural maps, provided an estimate of 1,495,000 ha. According to their estimation, fen peatlands were dominant in Poland and constituted 92.4% of the peatland area, while transitional peatlands and raised bogs constituted 3.3%, and 4.3%, respectively. However, this estimation is likely an underestimation as it applied only to peat soils (and not all organic soils) and did not take into account peatlands <1 ha. In addition, the changes that occurred (since the 1950s) in the areas covered by organic soils were not taken into account, e.g. many soils have developed into mursh, mursh-like soils and black earths after drainage. As such, there is an urgent need to estimate the area occupied by organic soils, as well as the area covered by soils of "organic" origin that accompany organic soils in the landscape, which also deserve attention due to their large stores of organic C.

In the most recent assessments, i.e. Poland's National Inventory Report (Bebkiewicz et al., 2022), the area of organic soils (mainly developed from peats) is estimated at 1.3 million ha (Table 2), which equates to 4.3% of the land area. These soils are mainly covered by grassland vegetation and forests (Table 2). Organic soils on cropland constitute 12%, and other lands (wetlands and settlements) cover 2.5%. Approximately 84% of peatlands are drained, and peat accumulation may occur on only 202,000 ha (approximately 16%) (Joosten et al., 2012).

Organic soils mainly develop in depressions, where they form peatlands. In Poland, the largest area is occupied by rheophilic peats (fens) fed by fertile flowing waters. They occur as valley peatlands, and occupy large areas in central Poland in large rivers valleys (in the old glacial zone), where they co-occur with alluvial soils (Roj-Rojewski and Walasek, 2013; Kabała, 2022). However, there are numerous lake and lakeside peatlands in the young glacial zone in northern Poland. Low valley peatlands cover large areas in the Land of Great Valleys, where wide ice-marginal valleys (Wrocław-Magdeburg-Bremen, Głogów-Baruth-Hamburg, Warszawa-Berlin and Toruń-Eberswald (also called as the Noteć-Warta ice-marginal valley) have become peat-covered. Due to their importance for biodiversity, peatlands in the Narew and Biebrza valleys are protected in national parks. The eastern part of the Land of Great Valleys is Lublin Polesie, which contains numerous lakes and large areas of peatlands, swamps and meadows. Many carbonate peatlands can be found due to the carbonate nature of the mineral substrate (chalky rocks, loess) (Zawadzki, 1957). It should be noted that 52% of peatlands in Poland are underlain by limnic sediments, i.e. their origin is related to peat formation within lakes (Kotowski et al., 2017).

Table 2
Area of organic soils under various land use categories in Poland (Bebkiewicz et al., 2022), as reported in the Poland's National Inventory Report (2022)

Land use category*	Area [ha]	Share	
		Polish land area [%]	Organic soil area [%]
Forest land	338,490	1.09	25.38
Cropland	160,040	0.51	12.00
Grassland	801,840	2.57	60.13
Wetlands	23,500	0.08	1.76
Settlements	9,750	0.03	0.73
TOTAL	1333,620	4.28	100.00

* – according to Poland's National Inventory Report (2022)

The zonal distribution of peatlands and organic soils in Poland results from a distribution of land depressions (Żurek, 1987; Dembek et al., 2000; Łachacz, 2016). Peat and mursh soils formed as a result of drainage prevail. Limnic soils classified as the gyttja subtype are related to artificial drainage of lakes (e.g. Łachacz and Nitkiewicz, 2021), which explains why they are particularly abundant in the young glacial landscape. They are the result of a specific land management model, popular in the second half of the 19th century and the beginning of the 20th century in countries (regions) located south of the Baltic Sea.

Lands covered with organic soils have been used for a wide range of purposes. In Europe, peat soils and peat deposits have been extracted for heating, for plant bedding, mulching or fertilisation since the 10th century (in Poland since the 17th century with intensified excavation in the 19th century) (Ilnicki, 2002). Since the 1970s, the use of peat as a fuel has declined and peatlands are instead utilised for agricultural and horticultural purposes (peat-based growing media), which has led to the degradation of peat soils.

Agricultural use of organic soils has been frequently related to biomass production (hay for animals), grazing or arable crops. For grassland use, it was important to lower the groundwater level to approximately 30–80 cm and for arable use to 100–120 cm. In the first years of usage, the drained organic soils were fertile (abundant in N and P). However, excessive drainage initiated many negative physical and chemical processes, peat mineralisation and subsequent peatland subsidence, a reduced ability to retain water, and increased GHG emissions. Consequently, organic soils have become degraded and some have disappeared from the landscape when the organic matter component was completely mineralised.

7. Protection of organic soils in Poland

Organic soils are vulnerable to any natural or human interference, which may include climatic changes, artificial drainage, afforestation or deforestation, pollution, agricultural use, burning, or exclusion from previous agricultural use (Fenner and Freeman, 2011; Fenner et al., 2011; Glina et al., 2016b; Heller and Zeitz, 2012; Holden et al., 2004; Kalisz et al., 2010; Kalisz et al., 2015; Kalisz et al., 2021; Karpińska-Kołaczek et al., 2024; Łachacz et al., 2009, 2023; Mendyk et al., 2016; Markiewicz et al., 2015; Sim et al., 2023; Smólczynski et al., 2011; Sulwiński et al., 2020; Smólczynski et al., 2021).

Organic soils are protected under international agreements and conventions. Their unique role in the environment has been recognised by the Ramsar Convention of 1971 (in force in Poland since 1975), which proposed several activities to protect these unique habitats. The current European Union Council Directive 79/409/EEC (1979) (Birds Directive) and Council Directive 92/43/EEC (1992) (Habitats Directive) (which have been transposed into Polish law) placed an obligation on EU Member States to establish the Natura 2000 network, which is the EU's flagship biodiversity program, under which endangered species on the surface of peat soils, as well as flora and fauna habitats are conserved (Grzybowski and Glińska-Lewczuk, 2020).

In recent years, the approach to the utilisation and protection of organic soils in Poland has changed substantially, and is now directly focused on the use and protection of wetlands, including peatlands. In the late 1950s and 1960s, peatlands were treated as agricultural land (ordinance of Minister of Agriculture, 30 July 1960). Another important legislation for the protection of peatlands was the 1982 Act on the Protection of Agricultural and Forestry land (Act No. 11, item 79), which included an additional category, "peatlands being wastelands", as agricultural land, alongside arable land, grassland and forest land. Nowadays, peatlands in Poland are protected under several legislations (Act on the Protection of Agricultural and Forest land (1995), Act on the Protection of Nature (2004)) and by strategic plans and programs. The latter includes the Programme for the Protection and Sustainable Use of Biodiversity, specific plans for water management and drought prevention, a Strategy for the Protection of Wetlands, a strategy for rural development, agriculture and fishery, a strategic plan for adaptation in sectors and areas vulnerable to climate change, and the Common Agricultural Policy. The Strategy for the Protection of Wetlands (Jabłońska et al., 2021) contains proposed actions for the protection of wetlands, including peatlands and organic soils. With regard to organic soils, a 30% reduction in GHG emissions is targeted, as is the promotion of natural processes in soils, an improvement in water retention, as well as protection of the soils. The strategy explicitly identifies threats to organic soils (as well as threats to peatlands), such as drainage and inadequate protection that results in damage of lands, as well as the location of settlements on organic soils. These threats lead to increased oxidation within the soil and increased GHG emissions, extinction of various species that grow or live in/on organic soils, poor water retention functions or impaired ecosystem services.

The challenge for environmental managers is to restore damaged and degraded organic soils to self-sustaining naturally functioning ecosystems that are able to accumulate organic matter and retain nutrients (Vasander et al., 2003). Therefore, the activities that permit restoration in the first place should include the limitation of drainage, utilisation of organic soils as grasslands with a high moisture content (so-called wet farming), avoidance of ploughing and/or fertilisation, which enhance organic matter oxidation. In recent years, drained peatlands and organic soils have received special attention as they are recognised as one of the drivers of climate change (CO_2 emitters). Therefore, an emphasis has been placed on the preservation of existing natural sites and the restoration of drained areas. To substantially reduce CO_2 emissions, the fundamental functions of organic soils (ability to retain water, ecological functions and biodiversity) must be restored. Wet organic soils can mitigate floods and droughts, as well as filter water, thereby improving overall water quality. The key to protection of organic soils is the way that they are used. The most important factor is to maintain high moisture levels in the topsoil and use of wet or rewetted soils (e.g. Renger et al., 2002; Jurczuk, 2011). In order to protect organic soils from excessive mineralisation (thereby limiting negative changes in the soil), Okruszko (1979) developed a concept of prognostic soil-moisture complexes that enable water retention and the capillary properties of soils to be predicted after drainage. This concept was further developed by Szuniewicz (1979).

One of the ways to restore some of these functions and provide ecosystem services is to promote paludiculture (wet farming), which includes wet organic soils, for the agricultural production of reed and moss biomass (to use as plant bedding, roof cover, horticultural products, etc.), while simultaneously preserving the organic matter content in the soil. As with any land use, paludiculture also has negative aspects – peat accumulation, C storage and biodiversity functions may not be fully restored when the biomass is harvested. Moreover, farmers may not be fully aware of the economic opportunities offered by wet organic soils. In some cases, rewetting of organic soils may encounter difficulties, such as a requirement for formal permits to block drainage ditches. Furthermore, rewetting may result in eutrophication as mobile compounds (especially P and N) in mursh materials can migrate to ground and surface waters. The development of (a) local initiatives that explore new methods for the sustainable management of fen soils, and (b) new business models for farmers and producers is key to help meet future climate goals (Xu et al., 2018).

8. Future organic soils research

Our review of the literature revealed that there is a lack of a consistent database of peatland types, organic soil units and their current transformation status. For example, Jabłońska et al., (2021) attempted to estimate the area of peatlands based on the GIS Wetlands database and on a forest database and datasets from the Institute of Soil Science and Plant Cultivation in Puławy. In their approach, they did not take into account that the GIS Wetlands database excluded peatlands with an area <10 ha, while the metadata for GIS Wetlands were from the 1950s, and the database itself was from the 1990s, and therefore out of date. Moreover, the data included in the various databases may overlap leading to incorrect estimations. In this respect, strong cooperation between policy makers, researchers, farmers and stakeholders is critical. Recently, the Institute of Soil Science and Plant Cultivation in Puławy has made a step towards updating the spatial database of soils with organic origins, based on a soil-agricultural map. It is well-known among soil scientists in Poland that organic soils have been substantially transformed since the maps were first released. Some peat, mud or gyttja soils no longer exist as they were mineralised and transformed into mineral soils. In contrast, there are also areas where organic soils have been restored, which also requires revision.

Given the above, the most important current directions of research on organic soils should include updating the resources of the organic soils database and the soils rich in organic C that accompany them in the landscape (some can be described as post-peat soils). Such a database should be linked to the distribution of organic soil contours (updated soil maps). In addition to this overarching task, a number of detailed research aspects should be pursued (Łachacz et al., 2023). These include:

- Improvement of methods for field and laboratory identification of materials that form organic soils (Schulz et al., 2019; Wittnebel et al., 2021; Saurette and Deragon, 2023; Volungevicius and Amaleviciute-Volunge, 2023). The development of criteria to distinguish the various organic soil materials from mineral soils with a higher organic C content.
- Increased research on water conditions and trophism associated with folisols to better understand the functions and role of these soils in the environment.
- Development of protocols to monitor (using field studies and remote sensing techniques) the distribution of organic soils and their transformation status (degradation) caused by progressive drainage.
- Development of approaches to limit (inhibit) SOM mineralisation and GHG emissions from agriculturally used organic soils.
- Determination of the effects of rewetting on the soil processes and properties of mursh materials.
- Determination of the influence of the mineral component or subsoil on the properties and evolution of drained organic soils.
- Research on how the transformation of the organic and mineral components of drained organic soils impacts their physical properties, including structure, hydrophobicity and water retention capacity.
- Research on the effect of mursh development stage on the physico-chemical properties of those soils, including the availability of nutrients for plants.

Acknowledgements

The authors would like to thank Marek Drewnik and Tomasz Kaczmarek for sharing photos of the debris folisol and the hemic murshic soil, respectively. This research was financially supported by a Polish Ministry of Science and Higher Education subsidy for research activities to the Department of Soil Science and Microbiology, University of Warmia and Mazury, Olsztyn (30.610.005-110), to the Department of Soil Science and Microbiology of University of Life Sciences, Poznań (506.101.01.00) and to the Institute of Soil Science, Plant Nutrition and Environmental Protection, Wrocław University of Environmental and Life Sciences.

References

Bebkiewicz, K., Boryń, E., Chłopek, Z., Doberska, A., Jędrysiak, P., Kargulewicz, I., Olecka, A., Rutkowski, J., Sędziwa, M., Skośkiewicz, J., Szczepański, K., Walęzak, M., Waśniewska, S., Zimakowska-Laskowska, M., Żaczek, M., 2022. Poland's national inventory report 2022 greenhouse gas inventory for 1988–2020, Ministry of Climate and Environment, Warsaw, Poland.

Becher, M., 2013. Organic matter transformation degree in the soils of the upper Liwiec river. Rozprawa Naukowa Uniwersytetu Przyrodniczo-Humanistycznego w Siedlcach, No. 125, 158 pp. (in Polish with English summary)

Becher, M., Pakula, K., Jaremko, D., 2020. Phosphorus accumulation in the dehydrated peat soils of the Liwiec River Valley. Journal of Ecological Engineering 21(5), 213–220. https://doi.org/10.12911/22998993/122673

Becher, M., Pakuła, K., Pielech, J., Trzcińska, E., 2018. Phosphorus resources and fractions in peat-muck soils. Environmental Protection and Natural Resources 29, 3(77), 1–6. https://doi.org/10.2478/oszn-2018-0012

Becher, M., Tołoczko, W., Godlewska, A., Pakuła, K., Żukowski, E., 2022. Fractional composition of organic matter and properties of humic acids in the soils of drained bogs of the Siedlce Heights in eastern Poland. Journal of Ecological Engineering 23, 208–222. https://doi.org/10.12911/22998993/146679

Becher, M., Kalembasa, D., Kalembasa, S., Symanowicz, B., Jaremko, D., Matyszczak, A., 2023. A new method for sequential fractionation of nitrogen in drained organic (peat) soils. International Journal of Environmental Research and Public Health 20, 2367. https://doi.org/10.3390/ijerph20032367

Bieniek, B., 1988. Changes of the chemical composition of peat soils occurring at a deep drainage under conditions of the Masurian Lake District. Roczniki Nauk Rolniczych, Ser. F, 80(2–4), 203–225. (in Polish with English summary)

Bochter, R., Zech, W., 1985. Organic compounds in cryofolists developed on limestone under subalpine coniferous forest, Bavaria. Geoderma 36, 2, 145–157. https://doi.org/10.1016/0016-7061(85)90034-5

Bogacz, A., 2005. Właściwości i stan przeobrażenia wybranych gleb organicznych Sudetów. [The properties and the stage of evolution of selected organic soils in the Sudety Mountains]. Zeszyty Naukowe Akademii Rolniczej we Wrocławiu, Nr 507, Rozprawy 226, 147 pp. (in Polish with English summary)

Bojko, O., Kabała, C., Mendyk, Ł., Markiewicz, M., Pagacz-Kostrzewa, M., Glina, B., 2017. Labile and stabile soil organic carbon fractions in surface horizons of mountain soils – relationships with vegetation and altitude. Journal of Mountain Science 14, 2391–2405. https://doi.org/10.1007/s11629-017-4449-1

Borowiec, J., 1990. Torfowiska Regionu Lubelskiego. [Peatlands of the Lublin Region]. PWN, Warszawa, 348 pp. + 4 maps. (in Polish)

Borówka, R.K., Sławińska, J., Okupny, D., Osóch, P., Tomkowiak, J., 2022. Mercury in the sediments of selected peatlands in Małopolska region. Acta Geographica Lodziensia 112, 61–76. https://doi.org/10.26485/AGL/2022/112/5

Cao, L., Song, J., Wang, Q., Li, X., Yuan, H., Li, N., Duan, L., 2017. Characterization of labile organic carbon in different coastal wetland soils of Laizhou Bay, Bohai Sea. Wetlands 37, 163–175. https://doi.org/10.1007/s13157-016-0858-0

Dębicka, M., Bogacz, A., Kowalczyk, K., 2021. Phosphorus behaviour and its basic indices under organic matter transformation in variable moisture conditions: A case study of fen organic soils in the Odra River Valley, Poland. Agronomy 11, 1997. https://doi.org/10.3390/agronomy11101997

Dembek, W., Piórkowski, H., Rycharski, M., 2000. Mokradła na tle regionalizacji fizycznogeograficznej Polski. [Wetlands in the context of the physical and geographical regionalisation of Poland]. Biblioteczka Wiadomości IMUZ 97, 1–135. (in Polish)

Długosz, J., Kalisz, B., Łachacz, A., 2018. Mineral matter composition of drained floodplain soils in north-eastern Poland. Soil Science Annual 69(3), 184–193. https://doi.org/10.2478/ssa-2018-0019

Dobrowolski, R., Mazurek, M.B., Osadowski, Z., Alexandrowicz, W.P., Pidek, I.A., Pazdur, A., Piotrowska, N., Drzymulska, D., Urban, D., 2019. Holocene environmental changes in northern Poland recorded in alkaline spring-fed fen deposits – A multi-proxy approach. Quaternary Science Reviews 219, 236–262. http://dx.doi.org/10.1016/j.quascirev.2019.05.027

Drewnik, M., Walas, J., Stolarczyk, M., 2015. Ogólna charakterystyka i właściwości gleb torfowiska stokowego na północnym skłonie Szerokiego Wierchu (Bieszczady Zachodnie). Roczniki Bieszczadzkie 23, 319–333. (in Polish with English summary)

Drewnik, M., Rajwaj-Kuligiewicz, A., Stolarczyk, M., Kucharczyk, S., Zelazny, M., 2018. Intra-annual groundwater levels and water temperature patterns in raised bogs affected by human impact in mountain areas in Poland. Science of the Total Environment 624, 991–1003. https://doi.org/10.1016/j.scitotenv.2017.12.203

Drozd, J., Kowaliński, S., Licznar, M., Licznar, S., 1987. Micromorphological interpretation of the physico-chemical processes in post-bog soils. Roczniki Gleboznawcze – Soil Science Annual 38(3), 121–137. (in Polish with English summary)

Everett, K.R., 1983. Histosols. [In:] Wilding, L.P., Smeck, N.E., Hall, G.F. (Eds), Pedogenesis and Soil Taxonomy II. The Soil Orders. Elsevier Scientific Publishers, Amsterdam, The Netherlands, 1–53.

Fenner, N., Freeman, C., 2011. Drought-induced carbon loss in peatlands. Nature Geoscience 4, 895–900.

Fenner, N., Williams, R., Toberman, H., Hughes, S., Reynolds, B., Freeman, C., 2011. Decomposition 'hotspots' in a rewetted peatland: implications for water quality and carbon cycling. Hydrobiologia 674, 51–66.

Forsmann, D.M., Kjaergaard, C., 2014. Phosphorus release from anaerobic peat soils during convective discharge. Effect of soil Fe:P molar ratio and preferential flow. Geoderma 223, 21–32.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. Environmental Reviews 19, 371–396.

Gałka, B., Kabała, C., Łabaz, B., Bogacz, A., 2014. Influence of stands with diverse share of Norway spruce in species structure on soil in various forest habitats in the Stołowe Mountains. Sylwan 158, 9, 684–694.

Gawlik, J., 1992. Water holding capacity of peat formations as an index of the state of their secondary transformation. Polish Journal of Soil Science 25(2), 121–126.

Ghani, A., Sarathchandra, U., Ledgard, S., Dexter, M., Lindsey, S., 2013. Microbial decomposition of leached or extracted dissolved organic carbon and nitrogen from pasture soils. Biology and Fertility of Soils 49, 747–755.

Glina, B., Bogacz, A., Wozniczka, P., 2016a. Nitrogen mineralization in forestry-drained peatland soils in the Stolowe Mountains National Park (Central Sudetes Mts). Soil Science Annual 67, 64–72. https://doi.org/10.1515/ssa-2016-0009

Glina, B., Bogacz, A., Gulyás, M., Zawieja, B., Gajewski, P., Kaczmarek, Z., 2016b. The effect of long-term forestry drainage on the current state of peatland soils: A case study from the Central Sudetes, SW Poland. Mires and Peat 18, 1–11. https://doi.org/10.19189/MaP.2016.OMB.239

Glina, B., Gajewski, P., Kaczmarek, Z., Owczarzak, W., Rybczynski, P., 2016c. Current state of peatland soils as an effect of long-term drainage – preliminary results of peatland ecosystems investigation in the Grojecka Valley (central Poland). Soil Science Annual 67, 3–9. https://doi.org/10.1515/ssa-2016-0001

Glina, B., Piernik, A., Hulisz, P., Mendyk, Ł., Tomaszewska, K., Podlaska, M., Bogacz, A., Spychalski, W., 2019. Water or soil – What is the dominant driver controlling the vegetation pattern of degraded shallow mountain peatlands? Land Degradation & Development 30, 1437–1448. https://doi.org/10.1002/ldr.3329

Glina, B., Piernik, A., Mocek-Płóciniak, A., Maier, A., Glatzel, S., 2021. Drivers controlling spatial and temporal variation of microbial properties and dissolved organic forms (DOC and DON) in fen soils with persistently low water tables. Global Ecology and Conservation 27, e01605. https://doi.org/10.1016/j.gecco.2021.e01605

Glina, B., Mendyk, L., Piernik, A., Nowak, M., Maier, A., Inselsbacher, E., Glatzel, S., 2022. Local weather conditions determine DOC production and losses from agricultural fen soils affected by open-pit lignite mining. Catena 211, http://dx.doi.org/10.1016/j.catena.2021.106012

Gnatowski, T., Szatyłowicz, J., Brandyk, T., Kechavarzi, C., 2010. Hydraulic properties of fen peat soils in Poland. Geoderma 154, 188–195. https://doi.org/10.1016/j.geoderma.2009.02.02

Gnatowski, T., Ostrowska-Ligęza, E., Kechavarzi, C., Kurzawski, G., Szatyłowicz, J., 2022. Heat capacity of drained peat soils. Applied Sciences 12, 1579. https://doi.org/10.3390/app12031579

Grosse-Brauckmann, G., Schäfer, W., Wittmann, O., 1995. Nochmals: Zur systematik und kartierung von moorböden. [Once more: On classification and mapping of peat soils]. Telma 25, 35–55.

Grzybowski, M., Glińska-Lewczuk, K., 2020. The principal threats to the peatlands habitats, in the continental bioregion of Central Europe – A case study of peatland conservation in Poland. Journal for Nature Conservation 53, 125778. https://doi.org/10.1016/j.jnc.2019.125778

Harris, L.I., Richardson, K., Bona, K.A., Davidson, S.J., Finkelstein, S.A., Garneau, M., Ray, J.C., 2022. The essential carbon service provided by northern peatlands. Frontiers in Ecology and the Environment 20, 222–230. https://doi.org/10.1139/facets-2022-0126

Hedberg, P., Kozub, L., Kotowski, W., 2014. Functional diversity analysis helps to identify filters affecting community assembly after fen restoration by top-soil removal and hay transfer. Journal for Nature Conservation 22, 1, 50–58. https://doi.org/10.1016/j.jnc.2013.08.004

Heller, C., Zeitz, J., 2012. Stability of soil organic matter in two northeastern German fen soils: the influence of site and soil development. Journal of Soils and Sediments 12, 1231–1240.

Hewelke, E., Szatyłowicz, J., Gnatowski, T., Oleszczuk, R., 2016. Effects of soil water repellency on moisture patterns in a degraded sapric Histosol. Land Degradation & Development 27, 955–964. https://doi.org/10.1002/ldr.2305

Holden, J., Chapman, P. J., Labadz, J. C., 2004. Artificial drainage of peatlands: hydrological and hydrochemical process and wetland restoration. Progress in Physical Geography 28, 95–123.

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R.B., Jones, M., MacDonald, G., ... & Yu, Z., 2020. Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. Proceedings of the National Academy of Sciences of the United States of America 117, 20438–20446.

Ilnicki, P., 2002. Torfowiska i torf [Peatlands and Peat]. Wydawnictwo Akademii Rolniczej im. Augusta Cieszkowskiego, Poznań, 606 pp. (in Polish)

Ilnicki, P., Zeitz, J., 2003. Irreversible loss of organic soil functions after reclamation. [In:] Parent, L-E., Ilnicki, P. (Eds), Organic soils and peat materials for sustainable agriculture. CRC Press, Boca Raton, USA, 15–32.

Ilnicki, P., Żurek, S., 1996. Peat resources in Poland. [In:] Lappalainen, E. (Ed.), Global peat resources. International Peat Society, Jyskä, Finland, 119–125.

IUSS Working Group WRB, 2006. World Reference Base for soil resources: a framework for international classification, correlation and communication. World Soil Resources Reports 103. FAO, ISRIC, IUSS, Rome.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports 106. FAO, Rome.

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps, 4th edition, International Union of Soil Sciences (IUSS), Vienna, Austria, 236 pp.

Jabłońska, E., Kotowski, W., Giergiczny, M., 2021. Projekt strategii ochrony mokradeł w Polsce na lata 2022–2032. Centrum Ochrony Mokradeł na zlecenie Generalnej Dyrekcji Ochrony Środowiska. (in Polish)

Joosten, H., Clarke, D., 2002. Wise use of mires and peatlands – background and principles including a framework for decision-making. International Mire Conservation Group/International Peat Society, Saarijärvi, Finland, 303 pp.

Joosten, H., Tapio-Biström, M.-L., Tol, S. (Eds), 2012. Peatlands – guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Mitigation of climate change in agriculture, Series 5, publishes by the Food and Agriculture Organization of the United Nations and Wetland International, Rome.

Jurczuk, S., 2011. Reclamation determinants of organic matter preservation in post-bog soils under meadows. Woda-Środowisko-Obszary Wiejskie, Rozprawy Naukowe i Monografie, No. 30, 81 pp. (in Polish with English summary)

Kabała, C., 2022. Origin, transformation and classification of alluvial soils (mady) in Poland – soils of the year 2022. Soil Science Annual 73, 3, 156043. https://doi.org/10.37501/soilsa/156043

Kabała, C., Bogacz, A., Łabaz, B., Szopka, K., Waroszewski, J., 2013. Różnorodność, dynamika i zagrożenia gleb. [In:] Knapik, R., Raj, A. (Eds), Przyroda Karkonoskiego Parku Narodowego, 91–126. (in Polish)

Kabała, C., Charzyński, P., Chodorowski, J., Drewnik, M., Glina, B., Greinert, A., ... & Waroszewski, J., 2019. Polish soil classification: Principles, classification scheme and correlations. Soil Science Annual 70(2), 71–97. https://doi.org/10.2478/ssa-2019-0009

Kacprzak, A., Drewnik, M., Uzarowicz Ł., 2006. Rozwój i kierunki przemian węglanowych gleb rumoszowych na terenie Pienińskiego Parku Narodowego. Pieniny–Przyroda i Człowiek 9, 41–50. (in Polish)

Kalisz, B., Łachacz, A., 2008. Morfologia i systematyka gleb mułowych w dolinie Omulwi i Rozogi na Równinie Kurpiowskiej. [Morphology and classification of mud soils in Omulew and Rozoga rivers valleys in Kurpie Plain]. Roczniki Gleboznawcze – Soil Science Annual 59(3/4), 89–96. (in Polish with English summary)

Kalisz, B., Łachacz, A., 2009. Content of nutrients, heavy metals and exchangeable cations in riverine organic soils. Polish Journal of Soil Science 42(1), 43–52.

Kalisz, B., Łachacz, A., 2023. Relations between labile and stable pool of soil organic carbon in drained and rewetted peatlands. Journal of Elementology 28(2), 263–278. http://dx.doi.org/10.5601/jelem.2023.28.1.3020

Kalisz, B., Łachacz, A., Głażewski, R., 2010. Transformation of some organic matter components in organic soils exposed to drainage. Turkish Journal of Agriculture and Forestry 34(3), 245–256. https://doi.org/10.3906/tar-0905-33

Kalisz, B., Łachacz, A., Głażewski, R., 2015. Effects of peat drainage on labile organic carbon and water repellency in NE Poland. Turkish Journal of Agriculture and Forestry 39(1), 20–27. https://doi.org/10.3906/tar-1402-66

Kalisz, B., Urbanowicz, P., Smólczyński, S., Orzechowski, M., 2021. Impact of siltation on the stability of organic matter in drained peatlands. Ecological Indicators 130, 108149. https://doi.org/10.1016/j.ecolind.2021.108149

Karpińska-Kołaczek, M., Kołaczek, P., Marcisz, K., Gałka, M., Kajukało-Drygalska, K., Mauquoy, D., Lamentowicz, M., 2024. Kettle-hole peatlands as carbon hot spots: Unveiling controls of carbon accumulation rates during the last two millennia. Catena 237, 107764. https://doi.org/10.1016/j.catena.2023.107764

Kasimir, A., He, H.X., Coria, J., Norden, A., 2018. Land use of drained peatlands: Greenhouse gas fluxes, plant production, and economics. Global Change Biology 24, 3302–3316.

Kimmel, K., Mander, Ü., 2010. Ecosystem services of peatlands: Implications for restoration. Progress in Physical Geography – Earth and Environment 34, 491–514.

Kinsman-Costello, L. E., Hamilton, S. K., O'Brien, J. M., Lennon, J. T., 2016. Phosphorus release from the drying and reflooding of diverse shallow sediments. Biogeochemistry 130, 159–176. https://doi.org/10.1007/s10533-016-0250-4

Kotowski, W., Dembek, W., Pawlikowski, P., 2017. Poland. [In:] Joosten, H., Tanneberger, F., Moen, A. (Eds), Mires and peatlands of Europe. Status, distribution and conservation. Schweizerbart Science Publishers, Stuttgart, Germany, 549–571.

Kowaliński, S., 1964. Gleby murszowe i ich przeobrażenia pod wpływem uprawy płużnej. [Moorsh soils and their metamorphoses effected by plough tillage]. Prace Wrocławskiego Towarzystwa Naukowego, Ser. B 124, 139 pp. (in Polish with English summary)

Kruczkowska, B., Błaszkiewicz, M., Jonczak, J., Uzarowicz, Ł., Moska, P., Brauer, A., Bonk, A., Słowiński, M., 2020. The Late Glacial pedogenesis interrupted by aeolian activity in Central Poland – Records from the Lake Gościąż catchment. Catena 185, 104286. https://doi.org/10.1016/j.catena.2019.104286

Kruczkowska, B., Jonczak, J., Słowińska, S., Bartczak, A., Kramkowski, M., Uzarowicz, Ł., Tyszkowski, S., Słowiński, M., 2021. Stages of soil development in the coastal zone of a disappearing lake – a case study from central Poland. Journal of Soils and Sediments 21, 1420–1436. https://doi.org/10.1007/s11368-021-02880-8

Krüger, J. P., Leifeld, J., Glatzel, S., Szidat, S., Alewell, C., 2015. Biogeochemical indicators of peatland degradation – a case study of temperate bog in northern Germany. Biogeosciences 12, 2861–2871. https://doi.org/10.5194/bg-12-2861-2015

Kulczyński, S., 1949. Peat bogs of Polesie. Mémoires de l'Académie Polonaise des Sciences et des Lettres, Classe des Sciences Mathématiques et Naturelles, Série B: Sciences Naturelles 15, Cracovie, 356 pp. + 46 phot.

Lasota, J., Błońska, E., 2021. C:N:P stoichiometry as an indicator of Histosol drainage in lowland and mountain forest ecosystems. Forest Ecosystems 8, 39. https://doi.org/10.1186/s40663-021-00319-7

Leifeld, J., Müller, M., Fuhrer, J., 2011. Peatland subsidence and carbon loss from drained temperate fens. Soil Use and Management 27, 170–176.

Leifeld, J., Klein, K., Wüst-Galley, C., 2020. Soil organic matter stoichiometry as indicator for peatland degradation. Scientific Reports 10, 7634. https://doi.org/10.1038/s41598-020-64275-y

Lemkowska, B., Sowiński, P., 2018. Limnic Rendzinas in the Mazurian Lakeland (NE Poland). Soil Science Annual 69(2), 109–120. https://doi.org/10.2478/ssa-2018-0011

Lehmann, J., Kleber, M., 2015. The contentious nature of soil organic matter. Nature 528, 60.

Lipka, K., 1978. Zanikanie torfowisk dawno zmeliorowanych w okolicach Rudnika nad Sanem, Leżajska i Przeworska. [Disappearance of peatlands reclaimed long ago in the vicinity of Rudnik on San, Leżajsk and Przeworsk]. Roczniki Nauk Rolniczych, Ser. F 79(4), 95–127. (in Polish with English summary)

Lipka, K., 2000. Torfowiska w dorzeczu Wisły jako element środowisk przyrodniczego. [Peat bogs in the Wisła river basin as an element of the natural environment]. Zeszyty Naukowe Akademii Rolniczej im. H. Kołłątaja w Krakowie, No. 255, 148 pp. + map. (in Polish with English summary)

Lipka, K., Zając, E., Hlotov, V., Siejka, Z., 2017. Disappearance rate of a peatland in Dublany near Lviv (Ukraine) drained in 19th century. Mires and Peat 19, 1–15. https://doi.org/10.19189/MaP.2017.OMB.279

Liu, H., Price, J., Rezanezhad, F., Lennartz, B., 2020. Centennial-scale shifts in hydrophysical properties of peat induced by drainage. Water Resources Research 56, e2020WR027538. https://doi.org/10.1029/2020WR027538

Lucas, R. E., 1982. Organic soils (Histosols). Formation, distribution, physical and chemical properties and management for crop production. Research Report 435 (Farm Science), Michigan State University, East Lansing, MI, USA, 77 pp.

Łabaz, B., Kabała, C., 2016. Human-induced development of mollic and umbric horizons in drained and farmed swampy alluvial soils. Catena 139, 117–126. https://doi.org/10.1016/j.catena.2015.12.013

Łachacz, A., 2001. Geneza i właściwości płytkich gleb organogenicznych na sandrze mazursko-kurpiowskim. [Origin and properties of shallow organogenic soils of the Mazury and Kurpie Plain]. Dissertations and Monographs of University of Warmia and Mazury in Olsztyn, No 49, 119 pp. (in Polish with English summary)

Łachacz, A., 2016. Peatlands in Poland – specificity, resources, conservation. [In:] Łachacz, A., Kalisz, B. (Eds), Polish National Committee of International Peatland Society – history, activities, achievements. Wydawnictwo Uniwersytetu Warmińsko-Mazurskiego w Olsztynie, Olsztyn, 11–22.

Łachacz, A., 2024. Polish peatland research in Polesye before the Second World War and its impact on the development of peatland knowledge. [In:] Urban, D., Dobrowolski, R., Jeznach, J. (Eds), Environmental engineering in Polesye. Book 3, Polish Polesye. Brest-Rivne-Warsaw-Ryazan, Warsaw University of Life Sciences Press, Warsaw, Poland, 27–41.

Łachacz, A., Kalisz, B., 2016. Polish contribution to the study of moorsh-forming process. [In:] Łachacz, A., Kalisz, B. (Eds), Polish National Committee of International Peatland Society – history, activities, achievements. Wydawnictwo Uniwersytetu Warmińsko-Mazurskiego w Olsztynie, Olsztyn: 115–130.

Łachacz, A., Nitkiewicz, S., 2021. Classification of soils developed from bottom lake deposits in north-eastern Poland. Soil Science Annual 72(2), 140643. https://doi.org/10.37501/soilsa/140643

Łachacz, A., Załuski, D., 2023. The usefulness of the Munsell colour indices for identification of drained soils with various content of organic matter. Journal of Soils and Sediments 23(11), 4017–4031. https://doi.org/10.1007/s11368-023-03604-w

Łachacz, A., Nitkiewicz, M., Kalisz, B., 2009. Water repellency of post-boggy soils with a various content of organic matter. Biologia, Section Botany 64(3), 635–639. https://doi.org/10.2478/s11756-009-0096-5

Łachacz, A., Kalisz, B., Sowiński, P., Smreczak, B., Niedźwiecki, J., 2023. Transformation of organic soils due to artificial drainage and agricultural use in Poland. Agriculture 13, 634. https://doi.org/10.3390/agriculture13030634

Magiera, T., Szuszkiewicz, M. M., Michczyński, A., Chróst, L., Szuszkiewicz, M., 2021. Peat bogs as archives of local ore mining and smelting activities over the centuries: A case study of Miasteczko Śląskie (Upper Silesia, Poland). Catena 198, 105063. https://doi.org/10.1016/j.catena.2020.105063

Malawska, M., Ekonomiuk, A., Wiłkomirski, B., 2006. Chemical characteristics of some peatlands in southern Poland. Mires and Peat 1, 1–14. http://pixelrauschen.de/wbmp/media/map01/map_1_2.pdf.

Maljanen, M., Sigurdsson, B. D., Guđmundsson, J., Óskarsson, H., Huttunen, J. T., Martikaine, P. J., 2010. Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences 7, 9, 2711–2738. https://doi.org/10.5194/bgd-6-6271-2009

Marcinek, J., 1976. Effect of drainage connected with the agriculture and forestry intensification on soil cover transformations. Zeszyty Problemowe Postępów Nauk Rolniczych 177, 73–157. (in Polish with English summary)

Marcinek, J., Spychalski, M., 1987. The influence of organic matter content in hydromorphic soils on their physical properties. Roczniki Akademii Rolniczej w Poznaniu, Melioracje 7, 19–33. (in Polish with English summary)

Marcinek, J., Spychalski, M., 1998. Degradacja gleb organicznych doliny Obry po ich odwodnieniu i wieloletnim rolniczym użytkowaniu. [Degradation of organic soils in Obra river valley after their drainage and many year agricultural use]. Zeszyty Problemowe Postępów Nauk Rolniczych 460, 219–236. (in Polish with English summary)

Markiewicz, M., Mendyk, Ł., Gonet., S. S., 2015. Soil organic matter status in agricultural soil sequence of former shoreline of disappearing Sumowskie lakes, North-Eastern Poland. Polish Journal of Soil Science 48(1), 65–78. http://dx.doi.org/10.17951/pjss.2015.48.1.65

Markiewicz, M., Gonet, S. S., Marszelewski, W., Mendyk, Ł., Sykuła, M., 2017. Differentiation of soils and land use changes in the vicinity of the disappeared Gardeja lake (Northern Poland). Soil Science Annual 68(3), 115–124. https://doi.org/10.1515/ssa-2017-0014

Maser, C., Trappe, J. M., 1984. The seen and unseen world of the fallen tree. General Technical Report 164, Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 56 pp.

Meissner, R., Leinweber, P., Rupp, H., Shenker, M., Litaor, M. I., Robinson, S., Schlichting, A., Koehn, J., 2008. Mitigation of diffuse phosphorus pollution during rewetting of fen peat soils: A Trans-European case study. Water, Air, and Soil Pollution 188 (1–4), 111–126. https://doi.org/10.1007/s11270-007-9528-4

Meller, E., 2006. Płytkie gleby organogeniczno-węglanowe na kredzie jeziornej i ich przeobrażenia w wyniku uprawy. [Shallow organogenic-calcareous soils on lacustrine chalk and their transformation resulted from cultivation]. Wydawnictwo Akademii Rolniczej w Szczecinie, Rozprawy Nr 233, 115 pp. (in Polish with English summary).

Mencel, J., Futa, B., Mocek-Plociniak, A., Mendyk, L., Piernik, A., Kaczmarek, T., Glina, B., 2022. Interplay between selected chemical and biochemical soil properties in the humus horizons of grassland soils with low water table depth. Sustainability 14(24). http://dx.doi.org/10.3390/su142416890

Mendyk, Ł., Markiewicz, M., Bednarek, R., Świtoniak, M., Gamrat, W. W., Krześlak, I., Sykuła M., Gersztyn, L., Kupniewska, A., 2016. Environmental changes of a shallow kettle lake catchment in a young glacial landscape (Sumowskie Lake catchment), North-Central Poland. Quaternary International 418, 116–131. http://dx.doi.org/10.1016/j.quaint.2015.10.008

Miklaszewski, S., 1930. Gleby Polski. [Soils of Poland]. 3rd edition. Komisja Wydawnicza Towarzystwa Bratniej Pomocy Studentów Politechniki Warszawskiej, Warszawa, 638 pp. (in Polish).

Mirosław-Grabowska, J., Obremska, M., Zawisza, E., Stańczak, J., Słowiński, M., Mulczyk, A., 2020. Biological and geochemical indicators of climatic oscillations during the Last Glacial Termination, the Kaniewo palaeolake (Central Poland). Ecological Indicators 114, 106301. https://doi.org/10.1016/j.ecolind.2020.106301

Mocek, A., 1978. Gleby o charakterze murszowym w otulinie Słowińskiego Parku Narodowego. Roczniki Gleboznawcze – Soil Science Annual 29, 3, 175–202. (in Polish with English summary)

Musielok, Ł., Kacprzak, A., Opyrchał, J., 2013. Właściwości i pozycja systematyczna gleb wytworzonych na ryolitach w Górach Kamiennych. Prace Geograficzne 135, 21–39.

Nagle, H. K., 2000. Folic debris slides near Prince Rupert, British Columbia. PhD Thesis, University of Alberta, Canada, 189 pp.

Nicia, P., Bejger, R., Zadrożny, P., Sterzyńska, M., 2018. The impact of restoration processes on the selected soil properties and organic matter transformation of mountain fens under Caltho-Alnetum community in the Babiogórski National Park in Outer Flysch Carpathians, Poland. Journal of Soil and Sediments 18, 2770–2776. https://doi.org/10.1007/s11368-017-1909-8

Norberg, L., Berglund, Ö., Berglund, K., 2018. Impact of drainage and soil properties on carbon dioxide emissions from intact cores of cultivated peat soils. Mires and Peat 21, 03, 1–14.

Okruszko, H., 1956. Zjawisko degradacji torfu na tle rozwoju torfowiska. [Phenomenon of peat degradation on the background of peatland development]. Zeszyty Problemowe Postępów Nauk Rolniczych 2, 69–111. (in Polish with English summary).

Okruszko, H., 1960. Gleby murszowe torfowisk dolinowych i ich chemiczne oraz fizyczne właściwości. [Muck soils of valley peatlands, and their chemical and physical properties]. Roczniki Nauk Rolniczych, Ser. F, 74(1), 5–89. (in Polish with English summary). Also published as: Translated from the Polish by USDA: TT67-56119; The Central Institute for Scientific, Technical and Economic Information, Warsaw, 79 pp.

Okruszko, H., 1964. Changes in phosphorus content of organic hydromorphic soils due to drainage. Roczniki Gleboznawcze – Soil Science Annual 14 (Supl.), 183–195.

Okruszko, H., 1969. Powstawanie mułów i gleb mułowych. Roczniki Gleboznawcze – Soil Science Annual 20, 1, 25–49. (in Polish with English summary)

Okruszko, H., 1976. Zasady rozpoznawania i podziału gleb hydrogenicznych z punktu widzenia potrzeb melioracji. [Principles of description and classification of hydrogenic soils in the view of their reclamation requirements]. Biblioteczka Wiadomości IMUZ 52, 7–53. (in Polish)

Okruszko, H., 1979. Zasady prognozowania warunków wilgotnościowych na glebach hydrogenicznych według koncepcji kompleksów wilgotnościowo-glebowych. [Rules for predicting soil moisture conditions according to the concept of Prognostic Soil-Moisture Complexes]. Biblioteczka Wiadomości IMUZ 58, 7–20. (in Polish)

Okruszko, H., 1993. Transformation of fen-peat soils under the impact of draining. Zeszyty Problemowe Postępów Nauk Rolniczych 406, 3–73.

Okruszko, H., Ilnicki, P., 2003. The moorsh horizons as quality indicators of reclaimed organic soils. [In:] Parent, L-E., Ilnicki, P. (Eds), Organic soils and peat materials for sustainable agriculture. CRC Press, Boca Raton (USA), 1–14.

Okruszko, H., Kozakiewicz, A., 1973. Humification and mineralization as mucking process elements in peat soils. Zeszyty Problemowe Postępów Nauk Rolniczych 146, 63–76. (in Polish with English summary)

Okruszko, H., Walczyna, J., 1970. Determination of abundance in phosphorus of meadow organic soils using the extraction in 0.5 n HCl. Roczniki Nauk Rolniczych, Ser. F, 77(3), 437–453. (in Polish with English summary)

Okupny, D., 2023. Geochemical characteristics of Late Glacial and Holocene biogenic sediments in central Poland and implications for reconstructing the palaeoenvironment. Acta Geographica Lodziensia 113, 47–76. https://doi.org/10.26485/AGL/2023/113/3

Okupny, D., Pawłowski, D., 2021. Elemental composition of biogenic sediments reveals palaeoclimatic changes during the Late Weichselian in a Central European river valley: A statistical approach. Catena 200, 105188. https://doi.org/10.1016/j.catena.2021.105188

Oleszczuk, R., Gnatowski, T., Brandyk, T., 2009. Critical peat soils moisture content as a criterion of irreversible swelling process. Acta Agrophysica 14(2), 403–412. (in Polish with English summary)

Oleszczuk, R., Łachacz, A., Kalisz, B., 2022. Measurements versus estimates of soil subsidence and mineralization rates at peatland over 50 years (1966–2016). Sustainability 14, 16459. https://doi.org/10.3390/su142416459

Oleszczuk, R., Regina, K., Szajdak, L., Höper, H., Maryganova, V., 2008. Impact of agricultural utilization of peat soils on the greenhouse gas balance. [In:] Strack, M. (Ed.), Peatlands and Climate Change. International Peat Society, Jyväskylä, Finland, 70–97.

Orzechowski, M., Smólczyński, S., Długosz, J., Kalisz, B., 2022. Spatial variability of water properties of soils formed from glaciolimnic deposits in Sepopol Lowland (Poland) – results from a field-scale study. Journal of Elementology 27(3), 533–544. https://doi.org/10.5601/jelem.2022.27.3.2279

Orzechowski, M., Smólczyński, S., Sowiński, P., Rybińska, B., 2013. Water repellency of soils with various content of organic matter in northeastern Poland. Soil Science Annual 64(2), 30–33.

Page, S. E., Baird, A. J., 2016. Peatlands and Global Change: Response and Resilience. Annual Review of Environment and Resources 41, 35–57.

Papierowska, E., Matysiak, W., Szatyłowicz, J., Debaene, G., Urbanek, E., Kalisz, B., Łachacz, A., 2018. Compatibility of methods used for soil water repellency determination for organic and organo-mineral soils. Geoderma 314, 221–231. https://doi.org/10.1016/j.geoderma.2017.11.012

Pauli, D., Peintinger, M., Schmid, B., 2002. Nutrient enrichment in calcareous fens: effects on plant species and community structure. Basic and Applied Ecology 3, 255–266.

Petera-Zganiacz, J., Dzieduszyńska, D. A., Milecka, K., Okupny, D., Słowiński, M., Michczyńska, D. J., Forysiak, J., Twardy, J., 2022. Climate and abiotic landscape controls of Younger Dryas environmental variability based on a terrestrial archive (the Żabieniec mire, Central Poland). Catena 219, 106611. https://doi.org/10.1016/j.catena.2022.106611

Piaścik, H., 1977. Przeobrażenia gleb torfowo-murszowych Pojezierza Mazurskiego ze szczególnym uwzględnieniem zmian w zawartości wapnia, żelaza i glinu. [Changes in peat-muck soils of the Mazurian Lakeland with particular regard to changes in the content of calcium, iron and aluminium]. Zeszyty Naukowe ART Olsztyn, Rolnictwo 23, 3–60. (in Polish with English summary)

Piaścik, H., Łachacz, A., 1997. The influence of dewatering and reclamation on water retention of peat soils in the sandy outwash landscape. Polish Journal of Soil Science 30(2), 7–14.

Piaścik, H., Łachacz A., 2001. The effects of the muck-forming process on the sorptive properties of peat soils. Polish Journal of Soil Science 34(2), 69–76.

Pons, L. J., 1960. Soil genesis and classification of reclaimed peat soils in connection with initial soil formation. Transactions of 7th International Congress of Soil Science, Madison, WI, USA, 4, 205–211.

Przesmycka, W., 1974. Occurrence of aluminium, iron and calcium phosphates in peat-muck soil profiles. Wiadomości Instytutu Melioracji i Użytków Zielonych 12(1), 117–138. (in Polish with English summary)

Renger, M., Wessolek, G., Schwaerzel, K., Sauerbrey, R., Siewert, C., 2002. Aspects of peat conservation and water management. Journal of Plant Nutrition and Soil Science 165, 487–493.

Rezanezhad, F., Price, J.S., Quinton, W.L., Lennartz, B., Milojevic, T., Van Cappellen, P., 2016. Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. Chemical Geology 429, 75–84. https://doi.org/10.1016/j.chemgeo.2016.03.010

Róg, Z., 1991. Micromorphologic aspects of the mucking process in differently utilized peat soils of the Experimental Station Biebrza. Wiadomości Instytutu Melioracji i Użytków Zielonych 16(3), 157–176. (in Polish with English summary)

Rydin, H., Jeglum, J., 2006. The biology of peatlands. Oxford University Press, 343 pp.

Renou-Wilson, F., Moser, G., Fallon, D., Farrell, C. A., Müller, C., Wilson, D., 2019. Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. Ecological Engineering 127, 547–560. https://doi.org/10.1016/j.ecoleng.2018.02.014

Riet Van de, B. P., Hefting, M. M., Verhoeven, J. T. A., 2013. Rewetting drained peat meadows: risks and benefits in terms of nutrient release and greenhouse gas exchange. Water, Air and Soil Pollution 224, 1440. https://doi.org/10.1007/s11270-013-1440-5

Roj-Rojewski, S., Walasek, M., 2013. Katena gleb mułowo-madowych w okolicy Suraża w Dolinie Górnej Narwi. Soil Science Annual 64, 2, 34–40.

Rząsa, S., 1963. Geneza i ewolucja mineralnych gleb murszowych na terenie odwadnianym. [Genesis and evolution of mineral muck soils in the terrain being drained]. Roczniki Wyższej Szkoły Rolniczej w Poznaniu 18, 151–223. (in Polish with English summary)

Sapek, A., Sapek, B., 1986. The use of 0.5 M sodium hydroxide extract for characterizing humic substances from organic formations. Roczniki Gleboznawcze – Soil Science Annual 37(2/3), 139–147. (in Polish with English summary)

Sapek, A., Sapek, B., 1992. Testing of grassland soils in Poland. Communications in Soil Science and Plant Analysis 23(17–20), 2165–2171. https://doi.org/10.1080/00103629209368732

Sapek, A., Sapek, B., 1997. Metody analizy chemicznej gleb organicznych. [Methods of chemical analyses of organic soils]. Materiały instruktażowe IMUZ, Falenty, No. 115, 80 pp. (in Polish)

Sapek, B., Sapek, A., 1987. Changes in the properties of humus substances and the sorption complex in reclaimed peat soils. International Peat Journal 2, 99–117.

Sapek, B., Sapek, A., 1993. Investigations of the specificity and effects of the secondary humification process of soils formed from various types of organic materials. Zeszyty Problemowe Postępów Nauk Rolniczych 406, 83–93.

Saurette, D.D., Deragon, R., 2023. Better recognition of limnic materials at the great group and subgroup levels of the Organic Order of the Canadian System of Soil Classification. Canadian Journal of Soil Science 103(1), 1–20. https://doi.org/10.1139/CJSS-2022-0030

Schulz, C., Meier-Uhlherr, R., Luthardt, V., Joosten, H., 2019. A toolkit for field identification and ecohydrological interpretation of peatland deposits in Germany. Mires and Peat 24, 1–20. https://doi.org/10.19189/MaP.2019.OMB.StA.1817

Sender, J., Różańska-Boczula, M., Urban, D., 2022. Active protection of endangered species of peat bog flora (*Drosera intermedia, D. anglica*) in the Łęczna-Włodawa Lake District. Water 14, 2775. https://doi.org/10.3390/w14182775

SGP 1, 1956. Przyrodniczo-genetyczna klasyfikacja gleb Polski ze szczególnym uwzględnieniem gleb uprawnych [A natural and genetical classification of Polish soils]. Roczniki Nauk Rolniczych 74, Seria D, 1–96. (in Polish with English summary)

SGP 2, 1959. Genetyczna klasyfikacja gleb Polski [Genetical classification of Polish soils]. Roczniki Gleboznawcze – Soil Science Annual 7(2), 1–103. (in Polish with English summary)

SGP 3, 1974. Systematyka gleb Polski [Polish soil classification]. Roczniki Gleboznawcze – Soil Science Annual 25(1), 1–148. (in Polish with English summary)

SGP 4, 1989. Systematyka gleb Polski [Polish soil classification]. Roczniki Gleboznawcze – Soil Science Annual 40(3/4), 1–150. (in Polish with English summary)

SGP 5, 2011. Systematyka gleb Polski [Polish soil classification]. Roczniki Gleboznawcze – Soil Science Annual 62(3), 1–193. (in Polish with English summary)

SGP 6, 2019. Systematyka gleb Polski [Polish soil classification]. Soil Science Society of Poland, Commission on Soil Genesis, Classification and Cartography. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Instytut Nauk o Glebie i Ochrony Środowiska Uniwersytetu Przyrodniczego we Wrocławiu; Polskie Towarzystwo Gleboznawcze. Komisja Genezy, Klasyfikacji i Kartografii Gleb, Wrocław–Warszawa, 292 pp. (in Polish)

Sim, T.G., Swindles, G.T., Morris, P.J., Baird, A.J., Gallego-Sala, A.V., Wang, Y., Zhang, H., 2023. Regional variability in peatland burning at mid-to high-latitudes during the Holocene. Quaternary Science Reviews 305. https://doi.org/10.1016/j.quascirev.2023.108020

Skiba, S., 2006. Pokrywa glebowa strefy wysokogórskiej Karpat i jej zagrożenia. Roczniki Bieszczadzkie 14, 201–214. (in Polish with English summary)

Skiba, S., Komornicki, T., 1983. Gleby organiczno-sufozyjne w Tatrach Polskich. Roczniki Gleboznawcze – Soil Science Annual 34, 4, 113–122. (in Polish with English summary)

Skiba, S., Drewnik, M., Szmuc, R., Prędki, R., 1998. Gleby Bieszczadzkiego Parku Narodowego. [Soils of the Bieszczady National Park]. Monografie Bieszczadzkie 2, 88 pp. + map. (in Polish with English summary)

Skiba, S., Kacprzak, A., Szymański, W., Musielok, Ł., 2011. Walory przyrodnicze górskich gleb rumoszowych. [Natural value of mountain debris soils]. Roczniki Bieszczadzkie 19, 335–348. (in Polish with English summary)

Skiba, S., Szymański, W., Prędki, R., 2014. Badania gleboznawcze w Karpatach Wschodnich i ich znaczenie w ochronie gleb Bieszczadzkiego Parku Narodowego. Roczniki Bieszczadzkie 22, 129–140. (in Polish with English summary)

Słowiński, M., Marcisz, K., Płóciennik, M., Obremska, M., Pawłowski, D., Okupny, D., Słowińska, S., Borówka, R., Kittel, P., Forysiak, J., Michczyńska, D. J., Lamentowicz, M., 2016. Drought as a stress driver of ecological changes in peatland – A palaeoecological study of peatland development between 3500 BCE and 200 BCE in central Poland. Palaeogeography, Palaeoclimatology, Palaeoecology 461, 272–291. http://dx.doi.org/10.1016/j.palaeo.2016.08.038

Smólczyński, S., Orzechowski, M., 2010a. Soils of ecotone zones of meltwater basins and slopes in a young glacial landscape of the Mazurian Lakeland. Soil Science Annual 61(4), 217–226.

Smólczyński, S., Orzechowski, M., 2010b. Sorptive properties of upper-silted organic soils in various landscapes of north-eastern Poland. Polish Journal of Soil Science, 43(2), 129–140.

Smólczynski, S., Kalisz, B., Orzechowski, M., 2011. Sequestration of humus compounds in soils of northeastern Poland. Polish Journal of Environmental Studies 20, 755–762.

Smólczynski, S., Orzechowski, M., Kalisz, B., 2015. Distribution of elements in soil catenas developed in ice-dammed lake and in morainic landscapes in NE Poland. Journal of Elementology 20(2), 417–434. https://doi.org/10.5601/jelem.2014.19.3.710

Smólczyński, S., Orzechowski, M., Kalisz, B., Sowiński, P., Urbanowicz, P., 2016. Soil air-water properties in catena of Sępopol Lowland. Polish Journal of Soil Science 49, 91–99.

Smólczyński, S., Kalisz, B., Urbanowicz, P., Orzechowski, M., 2021. Effect of peatland siltation on total and labile C, N, P and K. Sustainability 13, 8240. https://doi.org/10.3390/su13158240

Soil Survey Staff, 2022. Keys to Soil Taxonomy, 13th ed. USDA-Natural Resources Conservation Service, Washington, DC.,USA, 401 pp.

Soil Taxonomy, 1999. A basic system of soil classification for making and interpreting soil surveys. Soil Survey Staff, USDA-NRCS. Agriculture Handbook, No. 436. US Government Printing Office, Washington, DC. 869 pp.

Sowiński, P., Smólczyński, S., Orzechowski, M., 2004. Gleby obniżeń śródmorenowych jako bariery biogeochemiczne w krajobrazie rolniczym Pojezierza Mazurskiego. [Soils of mid-moraine depressions as a biogeochemical barriers in a agriculture landscape of Mazurian Lakeland]. Roczniki Gleboznawcze – Soil Science Annual 55(2), 365–372. (in Polish with English summary)

Sowiński, P., 2016. Variability of the content of macroelements in soils of a young glacial river valley – a geochemical landscape approach. Journal of Elementology 21(4), 1343–1358. https://doi.org/10.5601/jelem.2016.21.3.1109

Sowiński, P., Glińska-Lewczuk, K., Kalisz, B., Astel, A., 2016. Distribution of heavy metals in soils in a postglacial river valley – a geochemical approach. Environmental Engineering and Management Journal 15(6), 1323–1335.

Strzemski, M., 1980. Historia gleboznawstwa polskiego od zarania polskiego piśmiennictwa rolniczo-gleboznawczego do powstania Drugiej Rzeczypospolitej. [History of Polish soil science]. Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa, 224 pp. (in Polish)

Sulwiński, M., Mętrak, M., Wilk, M., Suska-Malawska, M., 2020. Smouldering fire in a nutrient-limited wetland ecosystem: Long-lasting changes in water and soil chemistry facilitate shrub expansion into a drained burned fen. Science of the Total Environment 746, 141142. https://doi.org/10.1016/j.scitotenv.2020.1411420048-9697

Suonan, J., Classen, A. T., Sanders, N. J., He, J. S., 2019. Plant phenological sensitivity to climate change on the Tibetan Plateau and relative to other areas of the world. Ecosphere 10, 1, 1–15.

Szatyłowicz, J., Gnatowski, T., Szejba, D., Oleszczuk, R., Brandyk, T., Kechavarzi, C., 2007. Moisture content variability in drained fen soil. [In:] Okruszko, T., Maltby, E., Szatyłowicz, J., Swiatek, D., Kotowski, W. (Eds), Wetlands: Monitoring, Modelling and Management. Taylor & Francis Group, London, UK, 113–120.

Szatyłowicz, J., Papierowska, E., Gnatowski, T., Szejba, D., Łachacz, A., 2024. Effect of vegetation cover and soil moisture on water repellency persistence of drained peat soils. Biologia. https://doi.org/10.1007/s11756-024-01735-0

Szuniewicz, J., 1979. Charakterystyka kompleksów wilgotnościowo-glebowych pod kątem parametrów systemu melioracyjnego. [Characteristics of soil-moisture complexes in terms of drainage system parameters]. Biblioteczka Wiadomości IMUZ 58, 29–50. (in Polish)

Szuniewicz, J., Szymanowski, M., 1977. Physico-hydrological properties and the formation of air-water conditions on distinguished sites of the Wizna fen. Polish Ecological Studies 3(3), 17–31.

Świtoniak, M., Kabała, C., Charzyński, P., 2016. Proposal of English equivalents for the soil taxa names in the Polish Soils Classification. Soil Science Annual 67(3), 103–116. https://doi.org/10.1515/ssa-2016-0013

Telega, P., 2022. Gleby organiczne ściółkowe – geneza, właściwości i rola ekologiczna w ekosystemach górskich. [Folic Histosols – genesis, properties and ecological role in mountain ecosystem]. PhD Thesis, Wrocław University of Life Science, 221 pp. (in Polish with English summary)

Tiemeyer, B., Kahle, P., 2014. Nitrogen and dissolved organic carbon (DOC) losses from an artificially drained grassland on organic soils. Biogeosciences 11, 4123–4137. https://doi.org/10.5194/bg-11-4123-2014.

Tiemeyer, B., Frings, J., Kahle, P., Köhne, S., Lennartz, B., 2007. A comprehensive study of nutrient losses, soil properties and groundwater concentrations in a degraded peatland used as an intensive meadow: Implications for re-wetting. Journal of Hydrology 345, 80–101.

Tobolski, K., 2000. Przewodnik do oznaczania torfów i osadów jeziornych. [A guide for identifying peats and lacustrine deposits]. Wydawnictwo Naukowe PWN, Warszawa, 508 pp. (in Polish)

Tobolski, K., Mocek, A., Dzięciołowski, W., 1997. Gleby Słowińskiego Parku Narodowego w świetle historii roślinności i podłoża. [Soils of the Słowiński National Park in the light of history of vegetation and geological substrate]. Wydawnictwo Homini, Bydgoszcz-Poznań, 183 pp. + 4 maps (in Polish)

Tołpa, S., Jasnowski, M., Pałczyński, A., 1967. System der genetischen Klassifizierung der Torfe Mitteleuropas. Zeszyty Problemowe Postępów Nauk Rolniczych 76, 9–99. (in German with English summary)

Tomaszewski, J., 1950. The essential conditions of the origination, development and metamorphosis of swampy soils. Roczniki Nauk Rolniczych 54, 607–629. (in Polish with English summary)

Tomaszewski, J., 1958. Processes in bog soil "from above" and "from below". Zeszyty Problemowe Postępów Nauk Rolniczych 17, 113–120. (in Polish with English summary)

Tuohy, P., O' Sullivan, L., Bracken, C. J., Fenton, O., 2023. Drainage status of grassland peat soils in Ireland: Extent, efficacy and implications for GHG emissions and rewetting efforts. Journal of Environmental Management 344, 118391. https://doi.org/10.1016/j.jenvman.2023.118391

Uggla, H., 1968. Bagienne i murszowe gleby gytiowiska Gązwa. [Bog and mull soils of the gyttja moorland at Gązwa]. Roczniki Gleboznawcze – Soil Science Annual 18(2), 369–414. (in Polish with English summary)

Uggla, H., 1976. „Rędziny" Pojezierza Mazurskiego. [Rendzinas in the Mazurian Lakeland]. Roczniki Gleboznawcze – Soil Science Annual 27(2), 113–125. (in Polish with English summary)

Urban, D., 2004. Siedliska hydrogeniczne oraz geneza i ewolucja wybranych torfowisk dolinowych Wyżyny Lubelskiej i Wołyńskiej. [Humidity habitats as well as the genesis and evolution of selected valley peat lands in the Lublin and Volhynia Uplands. Rozprawy Naukowe Akademii Rolniczej w Lublinie, No. 287, Lublin, 144 pp. (in Polish with English summary)

Vasander, H., Tuittila, E. S., Lode, E., Lundin, L., Ilomets, M., Sallantaus, T., ... & Laine, J., 2003. Status and restoration of peatlands in northern Europe. Wetlands Ecology and Management 11, 51–63. https://doi.org/10.1023/A:1022061622602

Volungevicius, J., Amaleviciute-Volunge, K. 2023. A conceptual approach to the Histosols profile morphology as a risk indicator in assessing the sustainability of their use and impact on climate change. Sustainability 15, 14024. https://doi.org/10.3390/su151814024

Walczyna, J., 1974. Organic-mineral compounds in drained hydrogenic soils and evolution trends of these soils. Roczniki Gleboznawcze – Soil Science Annual 25(2), 179–200. (in Polish with English summary)

Wittnebel, M., Tiemeyer, B., Dettmann, U., 2021. Peat and other organic soils under agricultural use in Germany: Properties and challenges for classification. Mires and Peat 27, 19.

Wondrausch, J., 1963. The rate of "mursh" process and moisture in relation to the chemical compostion of "mursh" soils formed out of low moor. Roczniki Gleboznawcze – Soil Science Annual 13(Supl.), 206–210. (in Polish with English summary)

Wójciak, H., 2004. Właściwości materii organicznej w odwodnionych glebach torfowych. [Properties of the organic matter in drained peat soils]. Dissertations and Monographs of University of Warmia and Mazury in Olsztyn, No 97, 71 pp. (in Polish with English summary)

Xu, J. R., Morris, P. J., Liu, J .G., Holden, J., 2018. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. Catena 160, 134–140. https://doi.org/10.1016/j.catena.2017.09.010

Zając, E., Zarzycki, J., Ryczek, M., 2018. Degradation of peat surface on an abandoned post-extracted bog and implications for re-vegetation. Applied Ecology and Environmental Research 16(3), 3363–3380, http://dx.doi.org/10.15666/aeer/1603_33633380

Zak, D., Gelbrecht, J., Zerbe, S., Shatwell, T., Barth, M., Cabezas, A., Steffenhagen, P., 2014. How helophytes influence the phosphorus cycle in degraded inundated peat soils – Implications for fen restoration. Ecological Engineering 66, 82–90. https://doi.org/10.1016/j.ecoleng.2013.10.003

Zawadzki, S., 1957. Investigations on the origin and evolution of bog soils rich in calcium carbonate in the Lublin District. Annales Universitatis Mariae Curie-Skłodowska, Sectio E, 12(1), 1–86. (in Polish with English summary)

Zawadzki, S., 1970. Relationship between the content of organic matter and physical properties of hydrogenic soils. Polish Journal of Soil Science 3(1), 3–9.

Ziółek, M., 2007. Phosphorus forms in organic soils with a varying degree of transformation (on the example of the Lublin Polesie region). Polish Journal of Soil Science 49(2), 179–194.

Żurek, S., 1987. Złoża torfowe Polski na tle stref torfowych Europy. [Peat deposits of Poland against the peat zones of Europe]. Dokumentacja Geograficzna 4, 1–184. (in Polish)

Geneza, przekształcenia i klasyfikacja gleb organicznych w Polsce

Słowa kluczowe

Torf
Gytia
Muł
Mursz
Systematyka gleb
Gleba Roku

Streszczenie

Polskie Towarzystwo Gleboznawcze wybrało gleby organiczne jako gleby roku 2024. Są to gleby zbudowane z materiałów zawierających ≥12% węgla organicznego, do których zaliczamy torfy, gytie i muły, a także gleby zbudowane z utworów ściółkowych (liście, szczątki drzewne i części roślin trawiastych), które zawierają ≥20% węgla organicznego. Specyficzne właściwości tych gleb, przede wszystkim wysoka zawartość węgla organicznego, niska gęstość objętościowa i wysoka porowatość, zdecydowanie odróżnia je od gleb mineralnych. W 6 wydaniu Systematyki gleb Polski wyróżniono cztery główne typy gleb organicznych, tj. gleby torfowe, gleby limnowe, gleby murszowe i gleby ściółkowe. Szacunkowa powierzchnia gleb organicznych w Polsce waha się od 4 do 5%. Gleby te zlokalizowane są głównie w bezodpływowych zagłębieniach terenu i dolinach rzecznych. Wyjątek stanowią gleby ściółkowe występujące głównie na terenach górskich. Wśród gleb organicznych zdecydowanie największą powierzchnię zajmują gleby torfowe i murszowe, użytkowane rolniczo. Gleby organiczne są uważane za największy naturalny lądowy rezerwuar węgla organicznego, jednak obserwowane zmiany klimatu, w połączeniu z intensywną działalnością człowieka wpływają negatywnie na ich potencjał do długotrwałego magazynowania węgla organicznego. W niniejszym artykule przeglądowym przedstawiono: (a) koncepcję gleb organicznych w Polsce; (b) aktualny schemat klasyfikacji gleb organicznych w Polsce oraz ich korelacji z międzynarodowymi systemami (WRB i Soil Taxonomy) (c) przegląd rozmieszczenia, użytkowania, zagrożeń i ochrony gleb organicznych w Polsce; oraz d) potencjalne przyszłe kierunki badań dotyczące gleb organicznych.