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A Conceptual Approach to the Histosols Profile Morphology as a Risk Indicator in Assessing the Sustainability of Their Use and Impact on Climate Change

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Abstract: In the context of climate change, the questions of the sustainability of peat soil use are particularly relevant. The evaluation of changes in the properties of soils (including histosols) using chemical methods is expensive, thus, their application possibilities are limited. Analyzing the morphology of histosol profiles would provide effective spatial analysis opportunities for assessing the extent of their anthropogenic transformation and impact on climate change. The key diagnostic horizons and their sequences for the identification of the risk group are the main results of the study. The analysis included 12 soil profiles, whose morphological structure was characterized using the WRB 2022 system of master symbols and suffixes for soil profile horizon descriptions. The analyzed profiles were excavated in forested (relatively natural), agricultural (agrogenized) and peat mining (technogenized) areas. The insights of this article in the discussion are based on the chemical analyses (pH KCl, N, P and K, soil organic carbon, dissolved organic carbon, mobile humus substance, humic and fulvo acids, C:N ratio and humification degree) of three histosol profiles. The main discussion is based on the results of the morphological analysis of the profiles. The results of this research allowed for the identification of a different structure of the histosol profile. The upper part of the histosol profile, which consists of O–H(a,e,i) horizons, indicates its naturalness. The murshic horizon (Hap) is the classic top horizon of the agricultural histosol profile, which is most affected by mineralization. The technogenized histosols have a partially destroyed profile, which is represented by the Ahτ/Haτ or only Haτ horizons at the top. The morphology of the histosol profile and the identification of the relevant horizons (Hap, Haτ and Ahτ) indicate its risks and presuppose a usage optimization solution. The most dangerous in the context of sustainable land use principles and climate change is the murshic horizon (Hap), which is uncovered after removing the horizon O. The risks of sustainable use of histosol are caused by measures that promote its microbiological activity, which is the maintenance of a drained state and cultivation. In the context of GHG emissions and sustainable use, the most favorable means would be the formation of the horizon O by applying perennial plants. Rewetting should be applied to those histosols whose removal from the agricultural or mining balance would provide maximum ecological benefits.

Keywords: histosol profile morphology; land use; agrogenization; drainage; mineralization

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1. Introduction

In the context of climate change and the loss of biodiversity, today's environmental and agricultural policies raise the questions about the sustainability of peat soil use. To achieve the goals of the Paris Agreement [1]—zero GHG emissions in 2050—all sectors, including agriculture, forestry, and land use change, must take measures. It is important to look for ways to make sustainable use of histosols, linking sustainability index (rate) with the indicators of organic matter properties of natural, agriculturally unaffected histosols. Histosols are sensitive to comprehensive economic use as their use intersects with the natural interests of agriculture, the environment (biodiversity, CO_2 emission control, climate change), industry and society.

The EU 2030 soil strategy [2] is the main document for the sustainable use of soils in the European region and purposefully distinguishes between organic and mineral soils to highlight different use priorities. In the territory of the EU, histosols cover only 8–10% but store 30% of the total soil carbon content and play a key role in contributing to the reduction of the effects of climate change in agriculture [3]. In many histosol-rich EU countries, more than 50% of peatlands are degraded [4]. Histosol degradation is caused by drainage, usually from agriculture, forestry or peat mining. Other problems that are associated with drained histosols include subsidence, reduced infiltration and loss of biodiversity [5]. Research conducted in Brazil [6] showed that the cultivation of peat soils after they have been drained negatively affects their chemical and physical properties: the amount of SOC decreases, DOC increases, and bulk density increases. Researchers from the countries of the European Union prepared a detailed report on the use of drained histosols, describing and comparing the similarities and differences between the socioeconomic and ecological issues faced by politicians and farmers when preparing proposals for low-emission land-use alternatives in peatlands [5,7]. Polish scientists [8] are conducting research in which they are investigating the sensitivity of organic matter to decomposition in histosols. It was established that drainage is the main factor determining changes in the physical properties and chemical composition of humus substances. Loss of organic matter, especially labile organic carbon fractions, is associated with histosol drainage. This is confirmed by lower amounts of total organic carbon, C:N values and higher E4:E6 values. With respect to these results, humic substances from undrained histosols were found to be richer in aromatic compounds and therefore can be considered more humified (and therefore more stable) than those from drained histosols [8,9]. Denmark has 25 years of experience in peatland restoration scope [10]. Its scientist-conducted studies did not confirm the hypothesis that plant community composition, species richness and diversity would improve with the age of restoration and eventually approximate the natural state of wetland vegetation [11]. To reduce the environmental impact of agricultural histosol drainage and prevent soil subsidence, the mineral deposit cover method is increasingly used in Switzerland [12]. Their study confirms the hypothesis that covering peat with a layer of mineral deposits results in lower carbon losses. An experiment conducted in Finland confirms that histosols emit higher greenhouse gas (GHG) emissions, especially CO_2 and N_2O, than mineral soils. Their study highlights the genetic diversity of cultivated histosols and highlights the importance of monitoring them to obtain reliable environmental assessments in the northern European region [13]. Different principles for their sustainable use must apply to organic soils, unlike mineral soils [10]. The main ones are the restriction of drainage systems in histosols, the restoration of ecosystems in them and the increase of biological diversity. Peatland drainage in Europe accounts for about 5% of the total EU GHG emissions [3,14]. Cultivated peatland areas still emit the highest GHG emissions from agricultural areas [15]. Restoration of drained peatlands alone could significantly reduce CO_2 emissions from agricultural land, with significant benefits for nature, biodiversity, and water conservation [5,9,10,14–18].

In summary, it can be said that the greatest attention is paid to changes in the chemical and physical properties of histosols, SOC emission and solving its management problems. Morphological studies of histosol profiles that investigate the issues of subsidence of histosols due to their drainage and use in agriculture [19] are rare. Often, they emphasize only changes in the topsoil.

Studies of the morphology of the histosol profile are relevant because they provide an opportunity to assess the damage caused to them due to their use and create an assumption for correction of the spatial calculations of SOC emission in the context of the impact on climate change. Chemical and physical studies of histosols (as well as mineral soils) are expensive and time-consuming and require other resources, while in-situ assessment of profile morphology allows effective differentiation of histosols into risk groups in the context of climate change and/or SOC emissions. These investigations form the basis for the creation of an efficient and easily applicable key for the anthropogenic transformation of histosols and a system for assessing the degree of risk. Such a system would make it possible to optimize the costs of laboratory research and to differentiate the obtained research results in a reasonable spatial way by objectively substantiating the influence of the use of histosols on climate change.

The aim of the study was to differentiate histosols according to their profile by determining the key diagnostic horizons and their sequences, which would be used to identify the risk group for their use. This would not only actualize the importance of profile morphology research in assessing CO_2 emissions from peat soils but also promote this direction of soil science in the context of both agriculture and ecology.

2. Sites and Methods

2.1. Description of the Research Object and the Study Site

The territory of Lithuania is in the mid-latitude, transitional climate zone; therefore, peat soils in its territory are formed and developed under wet (600–820 mm) and cold (6.0–7.5 °C) climate conditions [20,21]. The territory of Lithuania and the research objects of this study are in the following European mire regions [22]: the typical raised bog region and the continental fen and bog region. In Lithuania, soils that were classified as different types of histosols occupy about 7.87% of the country's territory (according to the GIS data of Lithuania's bogs and peatlands, 2011). Out of them, 2.38%, or circa 30%, are used for agricultural purposes. Presently, even 67% of histosols are drained and being actively used for different purposes: 38% for agriculture, 44% for forestry, 2% for peat mining and 5% for neglected drained areas.

Twelve peat soil profiles (Figure 1) were taken for the study as an illustration of the results of the investigation, which is conducted by the Lithuanian Research Centre for Agriculture and Forestry together with Vilnius University. About 50 profiles of histosols have been analyzed during these studies. In soil science, all peat soils are named histosols. Analyzed histosols and the morphology of their profiles were identified, classified and named according to the WRB 2022 classification, applying the system of master symbols and suffixes for soil profile horizon descriptions [23].

The research is based on the principle that the impact of human economic activity on the soil is identified through changes in its chemical and physical properties and morphology [24]. In mature natural forests, which grow in areas that have never been used for agriculture and have not been drained, this effect is minimal (only the chemical properties may be changed) or not identified at all. Agricultural areas are characterized by mixing of the upper soil horizons due to tillage, which changes the chemical, physical and morphological properties. Meanwhile, in peat mining areas, the soil profile is excavated and refilled during reclamation, so not only the physical properties but also the entire morphology of the peat soil profile change. Based on this approach, the histosol profiles illustrating the study were selected to reflect the natural environment, agricultural activities and peat extraction, as well as renaturalization and reclamation processes due to land use change. Therefore, the analyzed profiles of histosols were excavated in natural forested, agricultural (grassland and tillage areas), and peat mining areas.

In this article, natural histosols are interpreted as relatively natural since the assumption is made that due to climate change as well as the global direct and indirect impact of human economic activity, such histosols in the territory of Lithuania are practically unidentifiable or their identification is problematic and associated with their natural characteristics of chemical properties. Therefore, the analyzed histosol profiles are divided into three groups according to the nature and degree of their anthropogenic transformation (Figures 1 and 2):

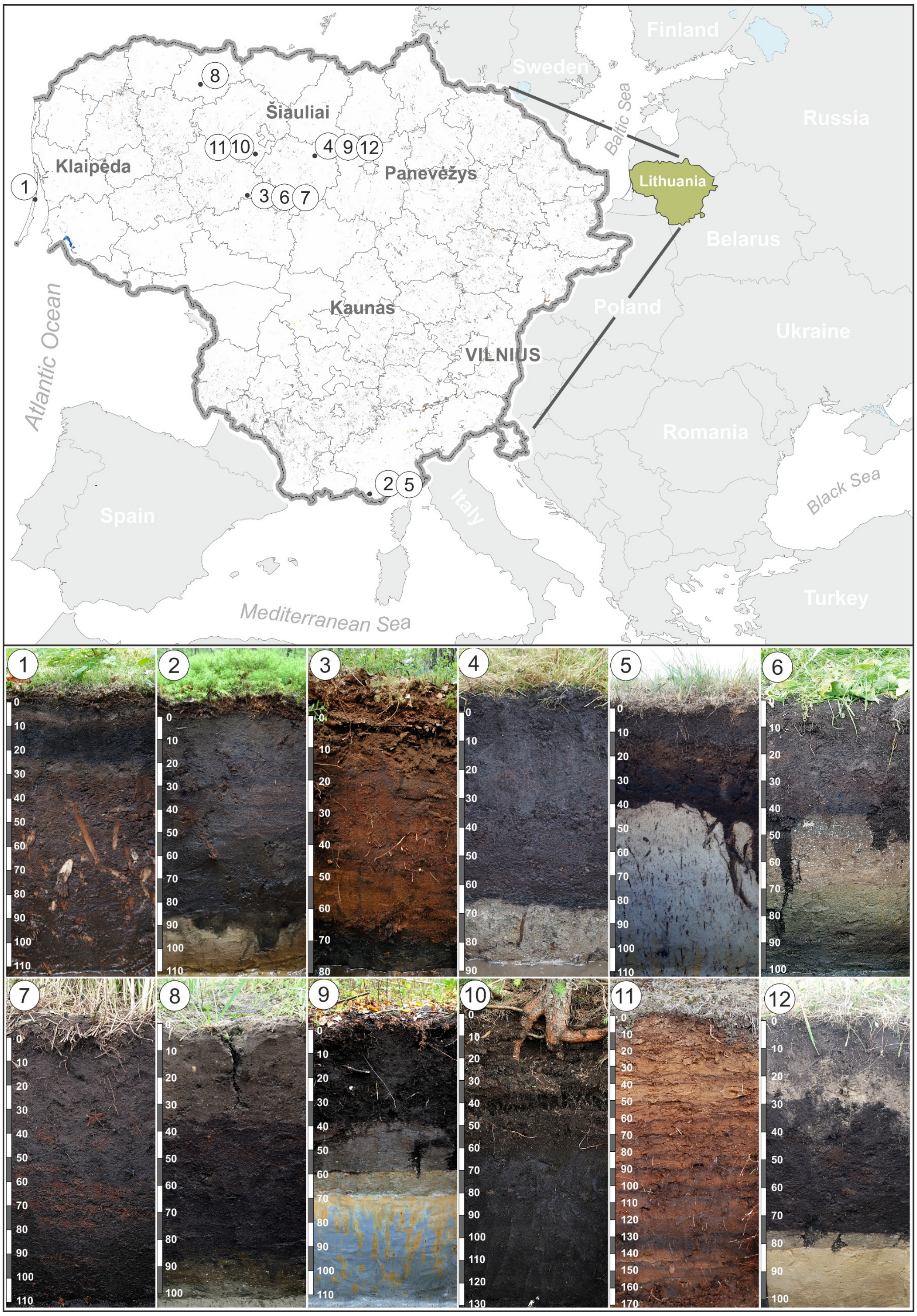

Figure 1. Localization of research objects. Coordinates and the names of the investigated histosols according to WRB 2022: 1. Hemic Drainic Rheic Histosol (Eutric, Mulmic, Mineralic), Neringa mun., Juodkrante, 55°33′20.78″ N 21°07′15.34″ E; 2. Hemic Rheic Dystric Histosol (Limnic), Varena mun., Kabeliai, 53°57′51.29″ N 24°17′15.33″ E; 3. Fibric Histosol (Dystric, Mulmic), Raseiniai mun., Siluva, 55°32′22.27″ N 23°17′50.48″ E; 4. Sapric Murshic Histosol (Eutric, Calcaric), Radviliskis mun., Radviliskis, 55°50′24.57″ N 20°28′34.65″ E; 5. Sapric Murshic Histosol (Dystric), Varena mun., Kabeliai, 53°57′21.91″ N 24°19′22.19″ E; 6. Sapric Murshic Histosol (Eutric, Calcaric, Limnic), Radviliskis mun., Saukotas, 55°35′25.01″ N 23°27′28.69″ E; 7. Hemic Murshic Histosol

(Eutric), Radviliskis mun., Saukotas, 55°32′36.51″ N 23°13′49.50″ E; 8. Sapric Histosol (Eutric, Aric, Limnic, Mineralic, Relocatic), Akmene mun., Balsiai, 56°06′01.43″ N 22°34′52.02″ E; 9. Sapric Drainic Histosol (Eutric, Limnic, Relocatic), Radviliskis mun., Radviliskis, 55°48′26.66″ N 23°29′38.00″ E; 10. Hemic Murshic Eutric Histosol (Relocatic), Šiauliai c. mun., Rekyva, 55°50′27.54″ N 23°18′13.67″ E; 11. Fibric Drainic Histosol (Dystric), Siauliai c. mun., Rekyva, 55°34′16.76″ N 23°17′27.90″ E; 12. Sapric Drainic Histosol (Eutric, Limnic, Mineralic, Novic, Relocatic, Transportic), Radviliskis mun., Radviliskis, 55°49′31.80″ N 20°29′18.06″ E.

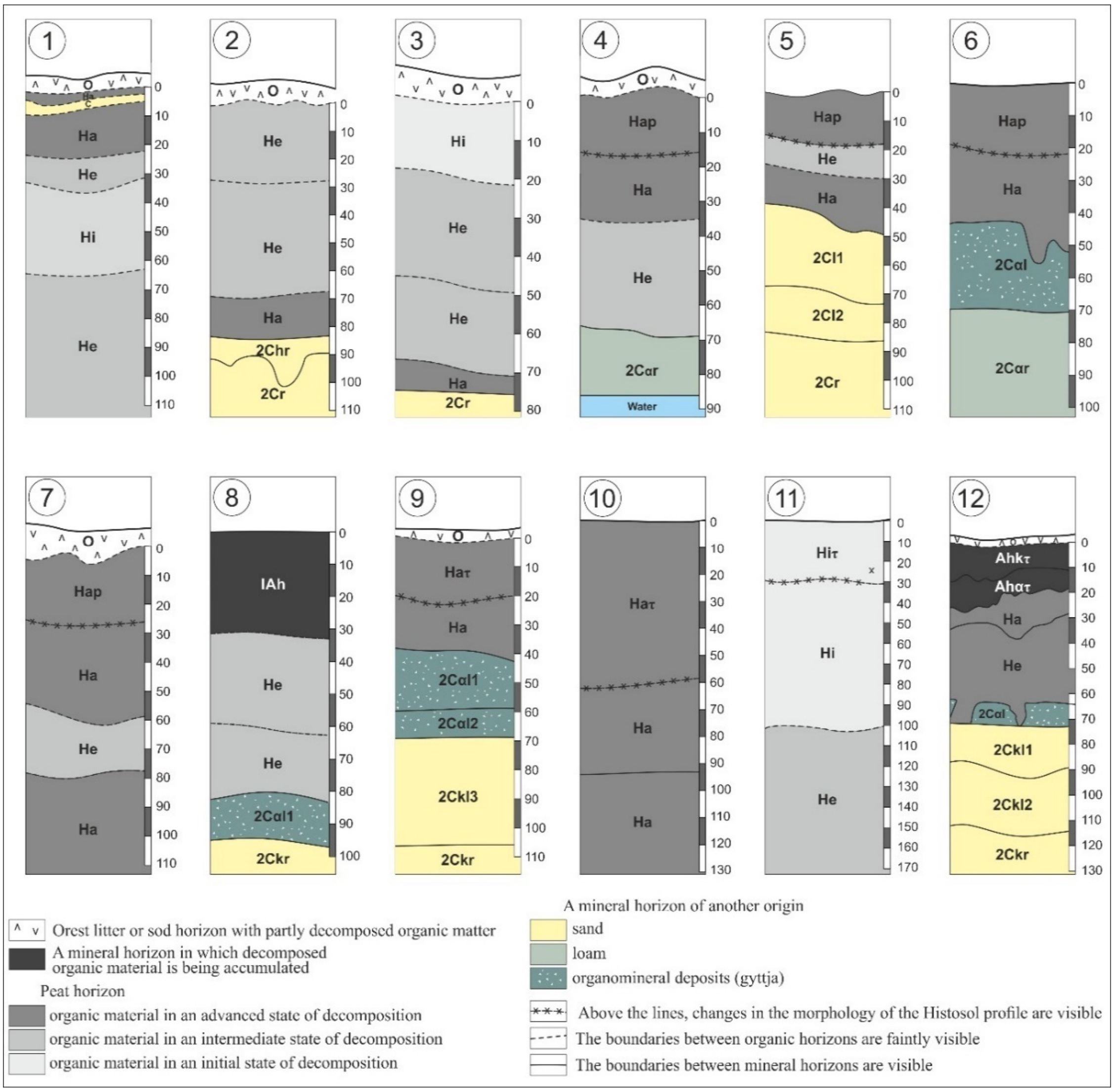

Figure 2. Soil profiles and their morphology were investigated. Descriptions of master symbols and suffixes of horizons: O—forest litter or sod horizon with partly decomposed organic matter, A—a mineral horizon in which decomposed organic material is being accumulated, H—peat layer, C—initial mineral horizon, I—a deluvial horizon of agricultural origin, a—organic material in an advanced state of decomposition, e—organic material in an intermediate state of decomposition, h—humic horizon with a significant amount of organic matter, i—organic material in an initial state of decomposition, k—secondary carbonates, l—capillary fringe mottling (gleying), p—horizon which is modified by cultivation (murshic), r—strong reduction conditions dominate, 2—a mineral horizon of another origin, α—primary carbonates, τ—human-transported natural material.

Relatively natural histosols (where the impact of human activity is very weak or indirect): (1)—Hemic Drainic Rheic Histosol (Eutric, Mulmic, Mineralic) (Juodkrante);

(2)—Hemic Rheic Dystric Histosol (Limnic) (Kabeliai); (3)—Fibric Histosol (Dystric, Mulmic) (Siluva).

Agrogenized histosols (where the impact of human activity on the morphology of the profile is visible only in the upper part of the profile): (4)—Sapric Murshic Histosol (Eutric, Calcaric) (Radviliskis); (5)—Sapric Murshic Histosol (Dystric) (Kabeliai); (6)—Sapric Murshic Histosol (Eutric, Calcaric, Limnic) (Saukotas); (7)—Hemic Murshic Histosol (Eutric) (Saukotas); (8)—Sapric Histosol (Eutric, Aric, Limnic, Mineralic, Relocatic) (Balsiai).

Technogenized histosols (where the impact of human activity on the morphology of the profile is visible in most or all of the profile): (9)—Sapric Drainic Histosol (Eutric, Limnic, Relocatic) (Radviliškis); (10)—Hemic Murshic Eutric Histosol (Relocatic) (Rekyva); (11)—Fibric Drainic Histosol (Dystric) (Rekyva); (12)—Sapric Drainic Histosol (Eutric, Limnic, Mineralic, Novic, Relocatic, Transportic) (Radviliskis).

2.2. Chemical Methods of Analyses

The insights in the article in the discussion part are based on the chemical analyses of profiles 4, 9 and 12 and the results of research conducted by other authors. All samples were air-dried. Then the samples were crushed, sieved through a 2 mm sieve and homogeneously mixed. For the analyses of humus content and composition, the soil samples were passed through a 0.2 mm sieve.

Chemical analyses were carried out at the Chemical Research Laboratory of the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry. Soil pH was determined in 1M KCl according to the standard ISO 10390:2005. Soil total nitrogen (N total) was determined by the Kjeldahl method, and plant-available phosphorus (P_2O_5) and potassium (K_2O) were determined by the Egner-Riehm-Domingo method (abbr. A—L). The total content of potassium (K) was determined using an atomic absorption meter, Analyst 200 (Perken Elmer, Waltham, MA, USA), after the mineralization with sulphuric acid. Soil organic carbon content (SOC) was determined by photometric procedure at a wavelength of 590 nm using the UV-VIS spectrophotometer Cary 50 (Varian) after wet combustion, according to Nikitin [25]. Mobile humic substances (MHS) and humic acids (MHA) were extracted using a 0.1 M NaOH solution (1:10) and determined according to Ponomareva and Plotnikova (1980). Dissolved organic carbon (DOC) was analyzed using an ion chromatograph SKALAR (Skalar Analytical B.V., Netherlands) ISO 8466. For the determination of DOC, the samples were shaken with distilled water at a ratio of 1:5 for 1 h. The automatic measurement procedure is based on the following reactions: the sample is acidified with nitrogen using a sulfuric acid solution. In this process, organic carbon is oxidized to carbon dioxide. The amount of carbon dioxide is measured by infrared detection in the 2–100 mg C L^{-1} range. The obtained results (mg C L^{-1}) are recalculated as % in soil.

3. Results

All human activities directly contribute to the morphological structure changes of soil profiles and are visible through the specific horizons (Figure 2). Moreover, qualitative and quantitative changes in the moisture regime and chemical and physical properties of histosols are caused by the same reasons.

Changes in all properties—chemical, physical, and morphological—are most visible in the top part of the histosol profile, i.e., primarily in the drainage-affected part. Both the nature and intensity of these changes in histosol profile differ depending on the intensity of the land use method (i.e., excavation, tillage, perennial grasses, self-renaturalization).

The naturalness of the histosol profile is assessed considering the original natural conditions in which histosols were formed on the territory of Lithuania. Because the territory of Lithuania is in conditions of excess moisture (>500 mm/m of precipitation), all histosols are formed in a forested landscape, so their natural profile should theoretically consist of O–H–. . .–H–2C(k)r horizons.

Horizon O (litter horizon), depending on the type of forest, consists of *histic* (peaty) or *mucky* (partially decayed herbaceous vegetation and leaves or needles) horizons; Depending on the bog type, the H horizons consist of highly (a), partially (e), or slightly (i) decomposed peat. The 2C(k)r horizon is identified only when the total layer of H horizons does not exceed 100 cm in thickness.

Relatively natural histosols are those peat soils that have slight or no morphological changes in the profile, i.e., only changes in chemical and/or physical properties predominate; the upper H horizon is dry due to the impact of reclamation systems. Reclamation is one of the most widespread means for soil cultivation in Lithuania. The afforested histosols (circa 290 thousand ha of histosols) experience the weakest transformation. The morphology of the profile of these histosols is: O–H(a,e,i)–H((a,e,i)-(2Cr). Horizon O usually consists of peaty matter and needles. These are research objects 1,2,3 (Figure 2), in which, depending on the depth of the peat, a typical profile with a mineral reduction horizon 2Cr and a multi-layer structure of H horizons is formed, the degree of decomposition of which depends on the conditions of the natural development of the histosols, so it can contain both Hi, both He and Ha horizons. The main identifier of their naturalness is the absence of the *murshic* horizon (mineralized and granular peat material) (Hap) and the presence of a peaty forest floor, which are the horizon O. The sequence of H horizons according to the degree of peat decomposition is not important, as it reflects only the natural variation of natural conditions. Such peatlands are mostly identified in forests or on the edges of agricultural or mining areas, i.e., in areas affected by land reclamation, but no intensive economic activity is carried out in them.

Agrogenized histosolsare the most widespread histosols in the territory of Lithuania, which are related to agricultural territories. According to the prevalence (192 thousand ha), the most widely affected by human activities are the *Sapric Histosols* (i.e., fens) in agricultural territories where the transformation of the soil profile is strongly expressed. In comparison, the *Fibric Histosols* (112 ha) (i.e., bogs) are less affected. In both cases, soil is characterized by a *murshic* horizon.

The transformation of the structure in the top part of the profile of agrogenized histosols (Figure 2, profiles 4–7) is typical. Drying of the topsoil due to targeted reclamation and the formation of a specific *murshic* horizon due to conventional tillage are noted. For the natural histosols in Lithuania, initial deep plowing (50 cm and deeper) and then long-term plowing at a depth of 25–30 cm were applied. As a result of the application of such a histosol cultivation system, intense peat mineralization and the formation of a specific granular structure—the *murshic* horizon—took place. This resulted in the subsidence of the upper peat layer and the formation of a typical 30 cm topsoil thickness, which is characteristic of the *murshic* horizon (Hap).

This profile morphological structure is typical for agrogenized histosol: Hap-H(a,e) -H(a,e)…H(a,e)- (2Cr). As a result of reclamation, the uppermost of the 2Cr horizons (mineral horizons with reducing properties) can transform into *gleyic* mineral horizons, which are denoted by the index 2Cl (Figure 2, profiles 5, 9). If the agrogenized histosol is left for spontaneous or targeted renaturalization, due to the changed nature of land use, the horizon O (the forest floor, the "felt" of the perennial meadow, which is usually also composed of the roots of herbaceous vegetation) is formed, which is at the top of the profile. One of the most characteristic morphological signs that indicates the intensive and long-term use of histosol in agriculture is the formation of the *murshic* (Hap) surface horizon. Due to drainage and conventional tillage, peat mineralization takes place, and fine (106–38 μm) particles increase in the *murshic* horizon (Hap). During the decomposition of peat, the content of humus substances and nitrogen increases (Table 1, profile 4). This affects take place pH to increase [26]. Also, compared to natural peat horizons Ha and He, the C:N ratio decreases in the *murchic* horizon (Hap) [26], but HD increases at the same time.

Table 1. Morphological and chemical data of histosol profiles.

Horisons	Depth, cm	pH KCl	SOC %	N %	P %	K %	DOC %	MHS %	MHA %	MFA %	C:N	HD
Profile 4—Agrogenized histosol												
O	+5–0	-	-	-	-	-	-	-	-	-		
Hap	0–30	5.61	42.68	3.08	0.01	0.01	0.09	12.57	11.36	1.21	13.86	26.61
Ha	30–50	4.55	48.59	3.00	0.00	0.01	0.05	9.03	7.00	2.03	16.17	14.41
He	50–70	6.32	42.97	1.73	1.73	0.14	0.05	5.96	4.80	1.15	24.85	11.18
2Cαr	75–86	7.55	0.78	1.40	0.08	0.37	0.02	12.32	5.32	7.00		
2Cαr	86–95	7.68	0.77	1.10	0.07	0.32	0.02	12.58	4.55	8.03		
Profile 9—Technogenized histosol												
O	+3–0	-	-	-	-	-	-	-	-	-		
Haτ	0–20	5.06	24.45	1.81	0.00	0.12	0.05	14.20	11.23	2.97	13.49	45.90
Ha	20–40	5.64	29.19	1.94	0.00	0.03	0.10	9.01	3.33	5.68	15.07	11.41
2Cαl1	40–60	7.15	26.6	3.05	0.00	0.14	0.07	3.66	1.23	2.43		
2Cαl2	60–70	7.77	1.64	1.83	0.52	0.29	0.02	0.10	0.01	0.09		
2Ckl3	70–71	8.22	0.23	0.45	0.40	0.13	0.01	0.01	0.00	0.01		
2Ckl3	71–80	8.50	0.12	0.34	0.48	0.15	0.01	0.01	0.00	0.01		
2Ckr	100–120	8.65	0.17	0.32	0.45	0.18	0.01	0.01	0.00	0.01		
Profile 12—Technogenized histosols												
O	+2–0	-	-	-	-	-	-	-	-	-		
Ahkτ	0–10	6.97	9.11	0.75	0.81	0.33	0.05	50.29	13.39	36.90	12.08	147.11
Ah$\alpha\tau$	10–20	6.11	1.63	0.48	0.47	0.28	0.01	18.60	5.58	13.02	3.42	342.49
Ha	20–30	6.95	29.69	1.24	0.39	0.22	0.02	4.01	3.35	0.66	23.89	11.27
He	30–65	6.56	51.70	1.72	0.00	0.14	0.02	6.91	5.56	1.35	30.09	10.75
2Cαl	65–75	7.57	7.09	0.64	0.00	0.20	0.01	33.25	4.05	29.20		
2Ckl1	75–85	7.99	0.88	0.44	0.00	0.17	0.02	1.59	1.07	0.52		
2Ckl2	85–110	7.97	0.54	0.44	0.00	0.20	0.01	2.80	0.74	2.06		
2Ckr	110–130	7.98	1.89	0.45	0.00	0.35	0.05	1.65	1.16	0.49		

Generally, as a result of the application of agrochemical measures in the top layers of agrogenized sapric histosols, the pH acidity decreases and becomes close to 6, the amount of SOC and DOC increases [27] and there is a decrease in the concentration of N (Table 1, profile 4). This is also confirmed by the results of the study conducted by I. A. Dubrovina [26]. Phosphorus (P) and potassium (K) concentrations depend on applied or non-applied fertilization, so they cannot be considered characteristic signs of histosol agrogenization.

Histosols in agricultural areas are usually concentrated in small areas in interhills or spread along field edges, but they are always associated with relief depressions. Therefore, due to intensive convention tillage, it can be covered with humus layers of mineral soil—deluvial sediments (the IAh horizon is formed). In some cases, small areas of peat soil are completely buried (Figure 2, profile 8). In this case, the IAh-He-. . .-H-H-(2Cr) profile with the characteristic horizon IAh (Figure 2, profile 8) is formed. In the context of the territory of Lithuania, this is not a common occurrence, which is mostly related to the hilly relief and small bogs and plays a natural role in peat soil shielding. The profile illustrating this is demonstrated in panel 8 (Figure 2). The formation of such a profile because of unsustainable tillage is similar to the recultivation process of excavated sapric histosol when the excavated peat is covered with a humus layer, which is composed of organomineral deposits. In this work, recultivated histosols are classified as technogenized histosols.

Circa 30 thousand ha of different types of histosols (technogenized histosols) are excavated for peat material production in Lithuania. These histosols include peat soils that have lost part of their profile due to excavation and/or are purposefully buried with a mineral-organic soil layer to conduct recultivation or surface shaping. The formation of the technogenic profile is mostly related to peat mining and subsequent surface recultivation. These histosols are characterized by an incomplete morphological structure of the profile: Ahτ/Haτ-(H)-H-2Cl-(2Cr). In such soils, the top layer of peat is often dug out, leaving a thin (up to 50 cm) H layer. If the histosol continues to be exposed to mining techniques, a structureless homogenized layer Haτ in the top part of its profile is formed. If the soil is recultivated to change its purpose and later use it for agriculture, a mineral horizon Ahτ with a high amount of SOC is formed. In the context of agricultural activities, this soil becomes similar to mineral soil because its topsoil layer acquires the chemical properties typical of the topsoil of mineral soils (Table 1, profile 12): pH becomes higher than 6, SOC content decreases from 25–50% to 2–9% (reminiscent of a drained bog); strongly, due to the mineralization of organic matter, the amount of MHS and MFA increases; if mineral fertilizers are used, the amounts of P and K increase significantly compared to natural peat. In fact, only H horizons, buried (50 cm and deeper) in the central part of the profile, indicate the former histosol. As a result of targeted deep reclamation, these soils usually have lost the reduction horizon 2Cr (missing reduction properties), as well as not only most of the horizon’s H but also the protective horizon O, which can slowly begin to recover, leaving the soil for spontaneous renaturalization—forestrization. This is illustrated by profiles 9, 10, 11 and 12 in Figure 2.

4. Discussion

Although the horizons of the soil profile analyzed in this study are only one of the potential indicators for assessing the current changes in the environment and their impact on the future environment, they are also complex results of the formation and change of the environment [28,29]. For this reason, they can be used as potential indicators for environmental change risk assessment, but this cannot be absolute, and it is necessary to consider other key factors such as changes in land use and climate parameters, applied agrochemical, agrotechnical, melioration and other human activity measures [30]. The transformation of the morphology of the histosol profile is important not only in the context of its diagnostics but also in assessing the intensity and sustainability of histosol (peatland) use and interpreting landscape development in the short and long term [28].

The analysis of changes in the morphological and chemical properties of the histosol profile is important not only in the context of changes in soil formation and their development but also in assessing their impact on climate change, identifying the degree of their transformation, and calculating potential GHG emissions. When applying GIS technologies, such data enable accurate assessment of the extent of changes and the planning of measures to increase the sustainability of their use and policies for optimizing their use at national and international levels.

O–H(a,e,i) (Table 2). The horizon O in the top part of the soil profile (forest floor or grassland sod layer) plays a protective role by regulating the amount of moisture in the topsoil layer and air circulation. It is also the primary source of organic carbon in the soil, and primary processes of humification and mineralization are taking place. Even if a relatively natural histosol has experienced the effects of drainage but the peat layer (H) that forms it is not mineralized and cultivated, the O horizon on its surface plays a preventive role and the impact on climate change is minimal for such a histosol. Horizon O is characteristic of natural histosols unaffected by human economic activity (Figure 2, profiles 1–3). However, it is also formed in those histosols where spontaneous renaturalization takes place (after a decrease in economic activity), for example, when perennial grassland is formed (Figure 2, profiles 7, 12), or a spontaneous forest regrowth occurs (Figure 2, profile 9). The formation of this horizon eliminates or significantly reduces the risk of a histosol effect due to environmental changes.

Table 2. A theoretical model of histosol diagnostic horizons in the context of environmental impact assessment.

Degree of Histosol Anthropogenization	Diagnostic Horizon in the Top Part of the Profile	Land Use	An Indication of the Relative Degree of Risk	Environmental Condition, Comments
Natural (relatively natural) (Figures 1 and 2, profiles 1–3)	O–H(a,e,i)	Forest	Non-risk	Undrained
Agrogenized (Figures 1 and 2, profiles 4–7)	Hap	A ploughed field	High risk	Drained, convention tillage
		Grassland	Moderate risk	A sod horizon is forming, and the histosol has preserved gleyic properties (partially rewetted) in the subsoil part of the profile.
		Afforestation	Low risk (in the long term)	The effect is better the more mature the tree is. Targeted conifer species promote the effect (targeted renaturalization).
Technogenized * (Figures 1 and 2, profiles 8–12)	Ahτ/Haτ	A ploughed field	High risk	Drained, convention tillage
		Grassland	Moderate risk	A sod horizon is forming, and theh histosol has preserved gleyic properties (partially rewetted) in the subsoil part of the profile.
		The forest	Low risk (in the long term)	The effect is better the more mature the tree is. Targeted conifer species promote the effect (targeted renaturalization).
	Haτ/Hiτ	Mining	High risk	Destruction of histosols takes place, and the negative impact on the environment is maximal.

* Excavated histosols, which are not buried under the Ahτ horizon and used in agriculture, behave the same as agrogenized peat soil and should therefore be considered in the context of agricultural activities.

Hap (Table 2). The *murshic* horizon is the classic top horizon of the agricultural histosol profile, which is most affected by mineralization [26–29]. This is evidenced by its granular, loose structure [29]. The impact of this horizon on climate change should be assessed through the approach of existing uses and expected renaturalization measures of histosols.

Murshic horizons are formed during conventional tillage [27,28] (Figure 2, profiles 4–7). Peat material that forms the Ha horizon, regularly mixing with air and thus promoting its mineralization. Mineralization is also promoted by the loss of moisture and the lowering of the groundwater level due to land reclamation. Basically, without changing the nature of use, it is a continuous process that significantly contributes to GHG emissions from histosols. The *murshic* horizon (Hap) is covered with vegetation when conventional tillage is changed to perennial grassland use. This is primarily because the microclimate of the histosol surface changes, and in the root zone, depending on the species composition of the herbaceous vegetation, humification and CO_2 emission processes begin. This is also confirmed by research conducted in Sweden [31]. In grasslands older than 5 years, enough fallout begins to accumulate, and a sod horizon O is formed, which increases the protection level of histosol against mineralization (Figure 2, profiles 4, 7). The horizon O compensates for the lack of moisture that has occurred due to the reclamation of histosol. Moisture content, groundwater level and land use are important in reducing CO_2 emissions from histosols [31,32]. Histosol convention tillage is inseparable from the use of mineral fertilizers, which promote peat mineralization. Nevertheless, this is compensated by the increase in the amount of organic matter, so the use of mineral fertilizers in this case is evaluated ambiguously, and its negative impact should be considered more from an ecological point of view, such as the migration of nitrogen and phosphorus into groundwater (Table 1).

Afforestation as a measure is also relevant to protecting histosol from mineralization. However, if perennial grassland is a short-term perspective measure, afforestation is focused on long-term effects—the formation of leaf litter and O-horizon (Figure 2, profile 9). This land use forms a suitable microclimate, regulates the moisture regime of the top layer and ensures the accumulation of organic matter.

Afforestation is also criticized in the study by B. Kløve and co-authors [33], which states that this measure helps to reduce CO_2 emissions in the short term, but the effect on N_2O emissions is limited and reveals itself only in the long term. J. Järveoja [34] also critically assesses afforestation, stating that on average, both non-fertilized and fertilized Phalaris cultivation alternatives had a negative GWP and therefore a cooling effect on the atmosphere, whereas the no-management, afforestation and rewetting alternatives had a positive GWP and thus contributed to global warming. This assessment is based on the ratio of CO_2 emissions to CO_2 resorption in biomass growth. Research conducted in Latvia [35] draws attention to the complexity of the effects of afforestation. The conducted study shows that afforestation of drained excavated histosol with hard leaves increases CO_2 emissions in the short term, which is the main component of GHG. This is associated with the fact that the decomposition of litter has been faster in deciduous stands than in coniferous stands. However, this effect is offset in the long term, as CO_2 is sequestered in forest biomass, a continuously accumulating forest floor that stores moisture and covers and protects deeper histosol layers, thereby reducing GHG emissions from them. It follows from this that spontaneous afforestation with hardwoods (as pioneer communities) is less effective than afforestation with target species, e.g., conifers.

Ahτ/Haτ (A plowed field) (Table 2)—Shielding of histosols (Figure 2, profiles 8, 12) with a layer of mineral matter (Ahτ) fully protects peat layers from mineralization and GHG from their emission. However, the effectiveness of the measure depends on the quality of the horizon Ahτ (or, if it is a deluvial layer, horizon IAh) itself. The horizon Ahτ is often formed from local mineral sandy deposits mixed with mineralized peaty material; thus, it is characterized by a high content of humus and a low moisture content. This leads to intensive mineralization of humus and peaty materials (Ahτ). Therefore, in theory, the goals are different from the practical result.

Ahτ/Haτ (Grassland, Forest) (Table 2)—The effect of grassland and agroforestry measures on technogenized histosol, stabilizing organic matter and peat composition and slowing down mineralization can be evaluated in the same way as in agrogenized peat (i.e., the same mineralization and humification control processes are applied).

Haτ/Hiτ (mining) (Table 2): Peatland mining is not evaluated unambiguously, and the impact on the environment is complex: generation of CO_2 emissions, destruction of histosol and biological diversity, change of the groundwater level both in the peatland and in the surrounding areas, etc. The horizon Haτ in question indicates an irreversibly damaged histosol structure (Figure 2, profiles 9–11). It is difficult to answer what state of the histosol this horizon indicates, as it depends on the measures applicable to its recultivation. If we reconstruct the groundwater level and regime, the horizon Haτ has the potential to do so; if only the horizon Haτ is shielded with a layer of Ahτ, the potential is limited; if further land use is envisaged as agriculture and the groundwater level is left unrestored (we should restore at least partially), the potential is low.

Unambiguously assessing the question of the sustainability of the use of histosols in the context of the morphology of their profile, when diagnostic horizons are identified as risk factors, is exceedingly difficult. This is difficult to do even when we are talking in the context of one economic activity (e.g., mining). Different studies show a very wide and different spectrum of CO_2 emissions from mining peatlands [30]. According to D. Wilson [36], much of this variation can be attributed to differences in climate, drainage level, peat type, peat extraction methods, and the end use of the peat. Standard CO_2 values from different agricultural land uses are also discussed [37].

In summary, it can be stated that there is no single universal measure for sustainable use or recultivation of histosols, therefore, the morphology of their profiles and diagnostic, condition-indicating horizons must be interpreted carefully. Some measures are more suitable when we aim to maintain agricultural productivity, others when the aim is to restore ecosystems and form ecological land areas. Thus, we must focus on targeted, regulated renaturalization or recultivation measures, both in terms of rewetting and agroforestry or afforestation, etc.

Research conducted by J. Järveoja and co-authors [38] shows that controlled renaturalization and targeted recultivation measures have a significant impact on environmental changes, especially GHG emissions. Nevertheless, in their study, they conclude that rewetting of histosols after removing the peat layer significantly affects only on the reduction of N_2O emissions, while the effect on the C and GHG balances is limited.

It is important that the different land uses created or maintained in histosols fulfil the functions of ecological compensation, eco-service or bioproduction economics by integrating paludiculture farming into traditional forms of farming.

5. Conclusions

The morphology of the histosol profile and the identification of the relevant horizons (Hap, Haτ, Ahτ) indicate its risks and suggest further use. The most dangerous in the context of sustainable land use principles and climate change is the *murshic* horizon (Hap), which is uncovered after removing the horizon O.

The risks of sustainable use of histosols are due to measures that promote its microbiological activity, which include the maintenance of a drained state and cultivation during which additional oxygen is introduced into histosol. Basically, the most effective measure is rewetting, but this measure should not be associated only with flooding. However, we must not forget that the use of histosols in the context of sustainable development is a reconciliation of ecological, social and economic interests. Therefore, measures used for histosols, especially in agriculture, must be applied in such a way as to help maintain their economic activity and not violate the principles of their sustainable use.

In the context of GHG emissions, the most favorable means of maintaining and restoring the morphology of the histosol profile would be the formation of the O horizon by applying perennial plants. Rewetting should be applied to those histosols whose removal from the agricultural or mining balance would provide maximum ecological benefits. Therefore, the removal from economic balance should be attributed to histosols of bogs. The concept of ecological land use should be applied to the use of fen histosols.

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References

1. Paris Agreement to the United Nations Framework Convention on Climate Change, Treaties and other International Acts Series No. 16-1104. 2015. Available online: https://www.state.gov/wp-content/uploads/2021/05/16-1104-Environment-and-Conservation-Multilateral-Paris-Agreement.pdf (accessed on 7 September 2022).
2. European Commission. *Communication from the Commision to the European Parlament, the Council, the European Economic and Social Committee, and the Committee of Regions EU Soil Strategy for 2030. Rapiding the Benefitis of Healthy Soils for People, Food, Nature and Climate*; SWD (2021) 323 Final; European Commission: Brussels, Belgium, 2021.
3. Matysek, M.; Leake, J.; Banwart, S.; Johnson, I.; Page, S.; Kaduk, J.; Smalley, A.; Cumming, A.; Zona, D. Impact of fertiliser, water table, and warming on celery yield and CO_2 and CH_4 emissions from fenland agricultural peat. *Sci. Total Environ.* **2019**, *667*, 179–190. [CrossRef]
4. Tanneberger, F.; Appulo, L.; Ewert, S.; Lakner, S.Ó.; Brolcháin, N.; Peters, J.; Wichtmann, W. The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives. *Adv. Sustain. Syst.* **2021**, *5*, 2000146. [CrossRef]
5. Buschmann, C.; Röder, N.; Berglund, K.; Berglund, Ö.; Lærke, P.E.; Maddison, M.; Mander, Ü.; Myllys, M.; Osterburg, B.; van den Akker, J.J.H. Perspectives on agriculturally used drained peat soils: Comparison of the socioeconomic and ecological business environments of six European regions. *Land Use Policy* **2020**, *90*, 104181. [CrossRef]
6. Santos, O.A.Q.; Silva Neto, E.C.; Garcia, A.C.; Fagundes, H.S.; Diniz, Y.V.F.G.; Ferreira, R.; Pereira, M.G. Impact of land use on Histosols properties in urban agriculture ecosystems of Rio de Janeiro, Brazil. *Rev. Bras. Cienc. Solo* **2020**, *44*, e0200041. [CrossRef]
7. Ojanen, P.; Minkkinen, K. The dependence of net soil CO_2 emissions on water table depth in boreal peatlands drained for forestry. *Mires Peat* **2019**, *27*, 1–8.
8. Bogacz, A.; Glina, B.; Januszewska, K.; Midor, A.; Tomaszewska, K.; Podlaska, M.; Telega, P.; Dradrach, A. The effect of long-term peatlands drainage on the properties of soils in microrelief in the Dlugie Mokradlo bog (Central Sudetes—Sw Poland). *Pol. J. Soil Sci.* **2017**, *50*, 237–247. [CrossRef]
9. Szczepanski, M.; Szajdak, L.W.; Meysne, T. Impact of Shelterbelt and Peatland Barriers on Agricultural Landscape Groundwater: Carbon and Nitrogen Compounds Removal Efficiency. *Agronomy* **2021**, *11*, 1972. [CrossRef]
10. Hoffmann, C.C.; Zak, D.; Kronvang, B.; Kjaergaard, C.; Carstensen, M.V.; Audet, J. An overview of nutrient transport mitigation measures for improvement of water quality in Denmark. *Ecol. Eng.* **2020**, *155*, 105863. [CrossRef]
11. Baumane, M.; Zak, D.H.; Riis, T.; Kotowski, W.; Hoffmanna, C.C.; Baattrup-Pedersen, A. Danish wetlands remained poor with plant species 17-years after restoration. *Sci. Total Environ.* **2021**, *798*, 149146. [CrossRef]
12. Wang, Y.; Paul, S.M.; Jocher, M.; Espic, C.; Alewell, C.; Szidat, S.; Leifeld, J. Soil carbon loss from drained agricultural peatland after coverage with mineral soil. *Sci. Total Environ.* **2021**, *800*, 149498. [CrossRef]
13. Yli-Halla, M.; Lötjönen, T.; Kekkonen, J.; Virtanen, S.; Marttila, H.; Liimatainen, M.; Saari, M.; Mikkola, J.; Suomela, R.; Joki-Tokola, E. Thickness of peat influences the leaching of substances and greenhouse gas emissions from a cultivated organic soil. *Sci. Total Environ.* **2022**, *806*, 150499. [CrossRef] [PubMed]
14. Shirokova, L.S.; Chupakov, A.V.; Ivanova, I.S.; Moreva, O.Y.; Zabelina, S.A.; Shutskiy, N.A.; Loiko, S.V.; Pokrovsky, O.S. Lichen, moss and peat control of C, nutrient, and trace metal regime in lakes of permafrost peatlands. *Sci. Total Environ.* **2021**, *782*, 146737. [CrossRef]
15. Campbell, D.I.; Glover-Clark, G.L.; Goodrich, J.P.; Morcom, C.P.; Schipper, L.A.; Wall, A.M. Large differences in CO_2 emissions from two dairy farms on a drained peatland driven by contrasting respiration rates during seasonal dry conditions. *Sci. Total Environ.* **2021**, *760*, 143410. [CrossRef]
16. Montanarella, L.; Panagos, P. The relevance of sustainable soil management within the European Green Deal. *Land Use Policy* **2021**, *100*, 104950. [CrossRef]
17. Magiera, T.; Szuszkiewicz, M.M.; Michczynski, A.; Chrost, L.; Szuszkiewicz, M. Peat bogs as archives of local ore mining and smelting activities over the centuries: A case study of Miasteczko Śląskie (Upper Silesia, Poland). *Catena* **2021**, *198*, 105063. [CrossRef]
18. Wu, Y.; Zhang, N.; Slater, G.; Michael Waddington, J.; Lannoy, C.F. Hydrophobicity of peat soils: Characterization of organic compound changes associated with heat-induced water repellency. *Sci. Total Environ.* **2020**, *714*, 136444. [CrossRef] [PubMed]
19. Szajdak, L.W.; Jezierski, A.; Wegner, K.; Meysner, T.; Szczepanski, M. Influence of Drainage on Peat Organic Matter: Implications for Development, Stability and Transformation. *Molecules* **2020**, *25*, 2587. [CrossRef] [PubMed]
20. Kažys, J. Vidutinė metinė oro temperatūra. In *Lietuvos Nacionalinis Atlasas: I Tomas*; GIS-Centras Nacionaline Zemes Tarnyba Prie Zemes Ukio Ministerijos Vilniaus Universitetas: Vilnius, Lithuania, 2014; p. 69. (In Lithuania)
21. Bukantis, A. Klimatinis rajonavimas. In *Lietuvos Nacionalinis Atlasa: I Tomas*; GIS-Centras Nacionaline Zemes Tarnyba Prie Zemes Ukio Ministerijos Vilniaus Universitetas: Vilnius, Lithuania, 2014; p. 74. (In Lithuania)
22. Tanneberger, F.; Moen, A.; Barthelmes, A.; Lewis, E.; Miles, L.; Sirin, A.; Tegetmeyer, C.; Joosten, H. Mires in Europe—Regional Diversity, Condition and Protection. *Diversity* **2021**, *13*, 381. [CrossRef]
23. IUSS Working Group WRB. World Reference Base for Soil Resources. In *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022.
24. Skorupskas, R.; Volungevičius, J. Classification of anthropogenic soil transformation. *Geologija* **2011**, *4*, 165–177.
25. Nikitin, B.A. Methods for soil humus determination. *Agro Chem.* **1999**, *3*, 156–158. (In Russian)

26. Dubrovina, I.A. Change in the content of total carbon, nitrogen and phosphorus in the boreal soils of the Republic of Karelia when used in agriculture. *Vestn. Tomsk. Gos. Univ. Biol. Tomsk State Univ. J. Biol.* **2018**, *41*, 27–41. (In Russian) [CrossRef]
27. Łachacz, A.; Kalisz, B.; Sowiński, P.; Smreczak, B.; Niedźwiecki, J. Transformation of organic soils due to artificial drainage and agricultural use in Poland. *Agriculture* **2023**, *13*, 634. [CrossRef]
28. Okruszko, H.; Ilnicki, P. The moorsh horizons as quality indicators of reclaimed organic soils. In *Organic Soils and Peat Materials for Sustainable Agriculture*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2002; pp. 1–14.
29. Łachacz, A.; Kalisz, B. Polish contribution to the study of moorsh-forming process. In *Polish National Committee of International Peatland Society—History, Activities, Achievements*; Łachacz, A., Kalisz, B., Eds.; Wydawnictwo Uniwersytetu Warmińsko-Mazurskiego w Olsztynie: Olsztyn, Poland, 2016; pp. 115–130.
30. Heller, C.; Zeitz, J. Stability of soil organic matter in two northeastern German fen soils: The influence of site and soil development. *J. Soils Sediments* **2012**, *12*, 1231–1240. [CrossRef]
31. Norberg, L.; Berglund, Ö.; Berglund, K. Impact of drainage and soil properties on carbon dioxide emissions from intact cores of cultivated peat soils. *Mires Peat* **2018**, *21*, 1–14.
32. Intergovernmental Panel on Climate Change (IPCC). Drained inland organic soils. In *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2014; p. 354.
33. Kløve, B.; Berglund, K.; Berglund, Ö.; Weldon, S.; Maljanen, M. Future options for cultivated Nordic peat soils: Can land management and rewetting control greenhouse gas emissions? *Environ. Sci. Policy* **2017**, *69*, 85–93. [CrossRef]
34. Järveoja, J.; Laht, J.; Maddison, M.; Soosaar, K.; Ostonen, I.; Mander, Ü. Mitigation of greenhouse gas emissions from an abandoned Baltic peat extraction area by growing reed canary grass: Life-cycle assessment. *Reg. Environ. Chang.* **2013**, *13*, 781–795. [CrossRef]
35. Vanags-Duka, M.; Bardule, A.; Butlers, A.; Upenieks, E.M.; Lazdin, Š.A.; Purvin, A.D.; Lıcıte, I. GHG Emissions from Drainage Ditches in Peat Extraction Sites and Peatland Forests in Hemiboreal Latvia. *Land* **2022**, *11*, 2233. [CrossRef]
36. Wilson, D.; Dixon, D.S.; Artz, R.R.E.; Smith, T.E.L.; Evans, C.D.; Owen, H.J.E.; Archer, E.; Renon-Wilson, F. Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of Ireland and the United Kingdom. *Biogeosciences* **2015**, *12*, 5291–5308. [CrossRef]
37. Berglund, Ö.; Kätterer, T.; Meurer, K.H.E. Emissions of CO_2, N_2O and CH_4 from Cultivated and Set Aside Drained Peatland in Central Sweden. *Front. Environ. Sci.* **2021**, *9*, 630721. [CrossRef]
38. Järveoja, J.; Peichl, M.; Maddison, M.; Soosaar, K.; Vellak, K.; Karofeld, E.; Teemusk, A.; Mander, Ü. Impact of water table level on annual carbon and greenhouse gas balances of a restored peat extraction area. *Biogeoscience* **2016**, *13*, 2637–2651. [CrossRef]