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Topsoil organic carbon and soil pH across different peatland use types in Co-Offaly, Ireland

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Abstract

Land use changes in temperate peat soils significantly impact topsoil organic carbon (SOC) content and soil pH, with implications for ecosystem functioning and carbon storage. Therefore, assessing soil organic carbon (SOC) and pH is instructive for reducing global carbon emissions. In this study, peat soil samples were collected from 0-10 cm and 10-20 cm depths in Co-Offaly, Ireland, to examine the SOC and soil pH across various peatland use types, including grassland (improved and unimproved), forestry, industrial cutaway, and cutover bog. The results indicate that among the peatland use types, intensive grassland exhibited the lowest SOC content, likely due to intensive management practices such as grazing, fertilizer application, and ploughing. Additionally, the land use change significantly impacts the soil pH, with a trend in soil pH across the different land use types observed as improved grassland > unimproved grassland > industrial cutaway > forestry > cutover. A strong negative correlation was observed between SOC content and soil pH, indicating that increased soil pH levels are associated with decreased SOC in temperate peatlands. This research contributes valuable insights into the intricate interplay between land use, SOC, and soil pH, offering pertinent knowledge for strategies aimed at enhancing global carbon management efforts.

1. Introduction

Peatlands comprise a small portion of the Earth's land area, accounting for only 3%, yet, they contain a significant amount of the world's soil organic carbon at 30%, which plays a crucial role in the global climate system, serving as either a source or sink for greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4) (Couwenberg et al., 2010; Drösler et al., 2008; Strack et al., 2008). Nevertheless, over half of most countries' natural peatlands have been degraded (Apori et al., 2022a; Drösler et al., 2008). In Europe, it has been estimated that about 50 million hectares of natural peatlands have been degraded. The causes of the degradation have been attributed to direct factors such as logging, conversion to large-scale agriculture and industrial plantations, artificial drainage canals etc., either than indirect factors such as climate change or land-use policy (Dohong et al., 2017; Gaveau et al., 2014; Hergoualc'h and Verchot, 2014).

The construction of drainage canals can facilitate peatland conversion into different land use types, such as agriculture, plantations, forestry, and mining, by reducing the groundwater table (Dohong et al., 2017). Land use change through drainage results in the decomposition of the peat, vegetation removal (above and below ground biomass), and oxidation, which are the primary sources of soil organic carbon (SOC) decrease and CO_2 emissions into the atmosphere (Murdiyarso et al., 2021). According to the Food and Agriculture (FAO) database, in 2010, there were 250000 km^2 of drained organic soils under cropland and grassland worldwide, which resulted in total greenhouse gas (GHG) emissions (N_2O and CO_2) of 0.9 Pg CO_2eq yr^{-1} (Tubiello et al., 2013) as a result of SOC decrease. Therefore as land use changes become more tailored to specific locations, assessing soil organic carbon becomes progressively crucial (Klingenfuß et al., 2014).

In addition to peatland use, several extrinsic factors contribute to the dynamics of soil organic carbon (SOC) in peat soils. The vegetation type that covers the peatland has a significant impact on the levels of soil organic carbon (SOC), as different plant species contribute varying amounts of organic matter (Apori et al., 2022). Climate plays a pivotal role, with temperature affecting microbial activity and decomposition rates; warmer conditions can accelerate these processes, potentially reducing SOC (Dash et al., 2019). The water table's depth is a crucial factor that determines the equilibrium between anaerobic and aerobic conditions.

Peat soils constitute 21% of the entire land area in Ireland, with a peatland area of 1.564.650 hectares (Pike, 2021).

However, it is approximated that just 10% of raised bogs and 28% of blanket bogs remain in their natural state and the larger vast of the natural peatland has been converted to other land use changes. Within the Republic of Ireland, the county of Offaly consists of various peatland types (e.g., intact peat bogs, degraded peatlands) which have been converted to farmed peatland for grassland production (the grazing of cattle); forestry for the cultivation of forest trees such as pine, spruce sycamore; industrial cutaway for generation of electricity in condensing power plant and cutover bog for making of briquette for domestic heating (Creamer and O'Sullivan, 2018). Nevertheless, the peatland use types can have a substantial impact on the characteristics of the top layer of the peat soil, such as the content of the organic carbon present and the pH level, which in turn can have important implications for the processes of carbon sequestration and nutrient cycling.

Soil pH, a crucial factor affecting peatlands' biogeochemistry, has been observed to experience changes in response to peatland use changes (Apori et al., 2022; Hergoualc'h and Verchot, 2014). Land use changes accelerate the process of peat decomposition, thereby resulting in the release of organic acids, carbonates, bicarbonates, and hydroxides into the soil solution (Agus et al., 2020). This process can decrease soil pH, influencing nutrient availability, microbial activity, and vegetation cover of the peatland ecosystems.

Several studies have investigated the alteration of natural peatland on soil organic carbon in Ireland (Eaton et al., 2008; Jarmain et al., 2023; Wellock et al., 2011), with few of those studies focusing on the comparison of the soil organic carbon (SOC) under different peatland use types. Also, until now, extensive research has not examined the impacts of various peatland use types on the Co-Offaly region's topsoil organic carbon content and soil pH. Therefore, the primary objective of this study is to address the existing knowledge deficit by evaluating the effects of land use type on soil organic carbon and soil pH under grassland, forestry, cutaway, and cutover in Co-Offaly of Ireland. The hypothesis tested is that the topsoil organic carbon (SOC) and soil pH exhibit variations across distinct peatland use types, namely grassland (improved and unimproved), forestry, and industrial cutaway. We anticipate these differences based on the specific land management practices associated with each use type. Grassland areas, for instance, may demonstrate lower SOC levels due to vegetation disturbance and intensive grassland management (e.g., the regular application of lime and fertilizers, tillage, grazing etc). In contrast, forestry sites might show variations in SOC and soil pH influenced by tree species, root systems, and potential acidification from organic matter decomposition (Steffens et al., 2022; Wang et al., 2013). Industrial cutaway areas are expected to display distinct SOC and soil pH profiles owing to alterations in peatland structure and potential environmental impact. This refined hypothesis provides a more detailed rationale for anticipating variations in SOC and soil pH, aligning with the diverse characteristics of each peatland use type.

2. Methods

2.1. Study area and soil sampling

Our research was conducted in Co-Offaly, which is situated in the central region of the Republic of Ireland (Fig. 1). The county used to have a good representation of natural peatland, a distinctive feature of the Midlands landscape. Unfortunately, since the 1980s, most of the natural peatlands have been converted into grasslands, forests, and industrial areas for energy production and horticulture by reducing the groundwater table through drainage (Creamer and O'Sullivan, 2018; Hammond and Brennan, 2003). Our study's selected land use change includes the Industrial cutaway, cutover bogs, improved grasslands, unimproved grasslands, and forest plantations (spruce trees). Peat soil samples were obtained from pine plantations that have matured beyond 10 years. This selection was made to study the characteristics and composition of peat soil in well-established and older pine stands. The industrial cutaway bogs originated from a formally raised bog that was subjected to industrial peat extraction predominantly for power production in a condensing power facility. Although the extraction activities in these bogs have since ceased, earlier activities have resulted in

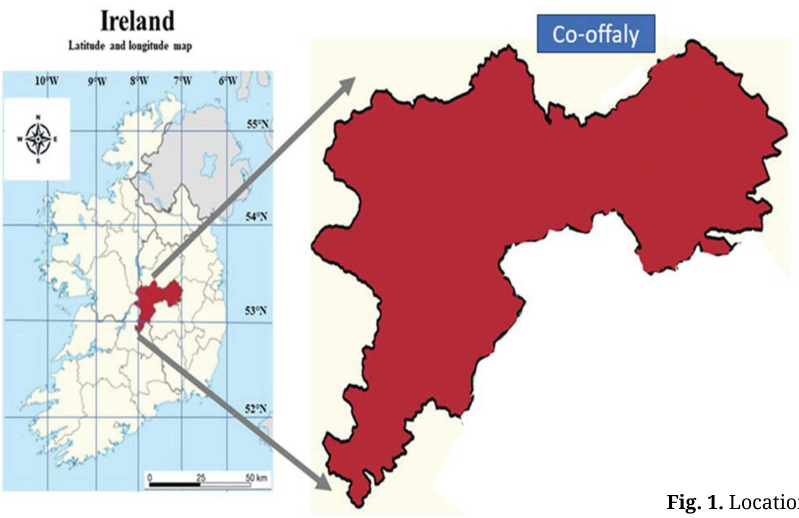

Fig. 1. Location of the study area in the republic of Ireland (Obeng et al., 2023).

the substantial removal of peat and vegetation cover. The county's annual air temperature varies from a minimum of 5.7°C to a maximum of 13.0°C while the average precipitation is 819 mm (Hammond and Brennan, 2003). The improved grassland has high coverage of ryegrass and white clover, in which slurry fertilizer and lime are frequently applied to enhance productivity, while the management practices for unimproved grassland are comparable to those of improved grassland, but they are not as intensive. The unimproved grassland has only been subjected to drainage and grass cultivation with limited soil fertilisation and livestock stocking. The hydrophobicity and humification index of the studied peatland use types have been well-described by Obeng et al. (2023).

2.2. Sampling and laboratory analysis

Between October 2021 and January 2022, 135 peat soil samples from various locations in Co-Offaly were collected. These samples were obtained from forest plantations (12 sites), grasslands (25 sites), cutover (2 sites) and industrial cutaway bogs (2 sites). Ten quadrats measuring 0.5 m × 0.5 m were placed at each site along a diagonal line within plots of approximately 50 m × 50 m. Before collecting peat soil samples, the vegetation present within each quadrant was trimmed. The peat soil samples were collected using a Russian peat corer with a diameter of 15 cm. The corner was used to extract samples at 20 cm intervals, which were subsequently separated into two distinct layers: 0–10 cm and 10–20 cm. Three composite peat soil samples were collected from each site, with ten cores taken from the ten quadrants and then placed into plastic self-sealed bags. In the laboratory, the peat soil samples were oven-dried at 60°C until constant weights were achieved and sieved to pass through a 2-mm mesh which was then used to determine the soil pH and the SOC. The soil pH was determined in a 1 : 2.5, soil: water suspension using a glass electrode of a pH meter (Sparks et al., 2020), and the loss of ignition method was used to determine the SOC (Agus et al., 2011). For the ignition loss, 1 gram of peat soil was combusted at 550°C for 4 hrs in a muffle furnace (Abella and Zimmer, 2007), after which the residual ash weight was obtained.

The following equation estimated the ash content (Pash,%):

$$Pash = \frac{Mash}{Mds} * 100 \qquad \text{Eq 1}$$

Ma_{sh} and M_{ds} represent the ash and dry mass of the peat soil. The percent SOC in the sample was then estimated using Eq 2

$$SOC\ (\%) = \frac{100 - Pash}{CF} \qquad \text{Eq 2}$$

Where SOC is the percent soil organic carbon and CF is the conversion factor to establish the SOC of the total organic matter (1.724) (Agus et al., 2011).

2.3. Data analysis

The data was analyzed using OriginPro learning edition software. The two-way analysis of variance (ANOVA) was performed to test differences in soil organic carbon and soil pH across land use types and the interaction between soil depths and peatland use type. Analysis of variance was performed to test the treatment effect for significance, and means were separated using Tukey HSD at the 0.05 significance level. Soil pH and soil organic carbon (SOC) content are essential ecological indicators of peatlands, and understanding the relationship between these two properties is crucial for sustainable land management of peatlands. Therefore, the Pearson correlation was used to identify the interrelationship between the soil pH and organic carbon.

3. Results

3.1. Soil pH

The two-way ANOVA indicated that the peatland use change had significant effects on soil pH (P < 0.0001), while the soil depth and the interaction of peatland use change and soil depth had no significant effect on the soil pH (Table 1).

In 0–10 cm depth, the highest soil pH was exhibited by the improved grassland (6.18), followed by unimproved grassland, cutaway bog, forestry, and cutover bog (4.08) (Fig. 2a). The soil pH in the 10–20 cm depth follows a similar trend to that of the 0–10 cm, such that the highest and the least soil pH was exhibited by the improved grassland (6.01) and the cutover bog (4.23), respectively (Fig. 2b). Regarding the grassland management type, the soil pH of the improved grassland (6.01) did not differ significantly (P > 0.05) in comparison with the unimproved grassland (5.85), while the industrial cutaway bog exhibited higher pH (5.48) as compared to the cutover bog (4.08) (Fig. 2b). In 0–20 cm, the pH varied significantly (P < 0.005) among the land use types. The pH ranged from 4.38 to 6.08, with the

Table 1.
Results of two-way ANOVA for the effect of land use type and soil depth on soil pH organic carbon.

	Soil pH		Soil organic carbon (%)	
	F	*Significant*^{X}	*F*	*Significant*^{X}
Peatland use type	83.85	****	69.29	****
Soil depth	1.72	NS	0.85	NS
Peatland use type *soil depth	0.086	NS	0.15	NS

Significant^X, and F values were obtained from two-way ANOVA. **** significant at P < 0.0001. df is Degrees of freedom.

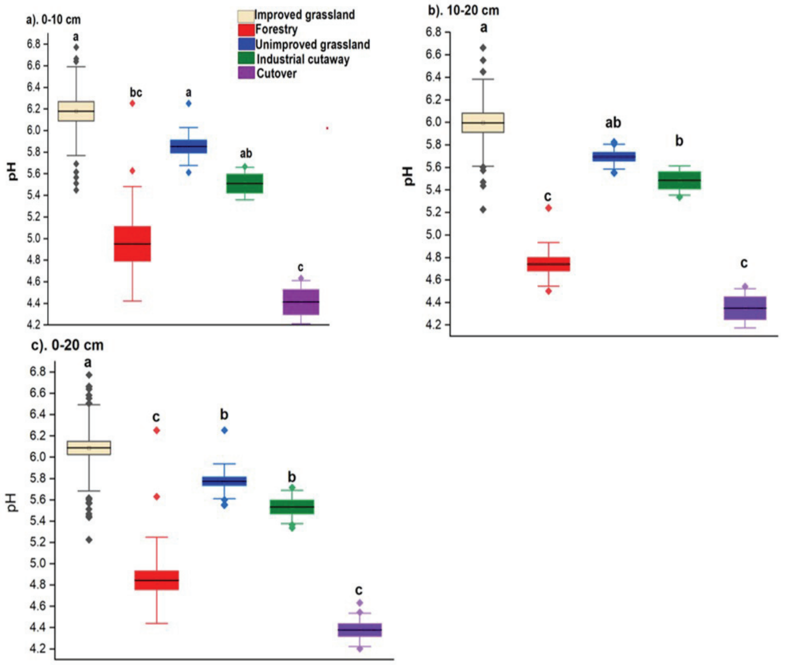

Fig. 2. Effects of land use type on soil pH. Asterisk marks (lower and upper) in the range represent the 1% and 99% percentiles, respectively. Asterisks outside the range represent outliers. Small rectangular boxes represent mean values. The same letters on the box are not significantly different at P 0.0 5 using Tukey HSD at the 0.05 significance level.

lowest and the highest recorded by the cutover bog and improved grassland, respectively (Fig. 2c). The soil pH followed the improved grassland > unimproved grassland > Industrial cutaway bog > forestry > active bog (Fig. 2c).

3.2. Soil organic carbon concentration

Two-way ANOVA indicated that soil depth (0-10 and 10-20 cm) and the interaction of the land use change and the soil depth exhibited a non-significant effect ($P > 0.05$) on SOC, whereas the land use type had a significant impact on SOC (Table 1). In the 0-10 cm depth, the SOC ranged from 41.63 to 54.51%, with the highest SOC obtained by the cutaway bog, followed by cutover bog, forestry, unimproved grassland, and improved grassland (Fig. 3a). The SOC among the two grasslands differs significantly, such that the improved grassland and the unimproved grassland exhibited SOC of 42.98% and 46.93%, respectively. In contrast, the cutaway and the cutover bog did not differ significantly ($P > 0.05$). A similar trend of the SOC was obtained in the 10–20 cm depth to that of the 0–10 cm depth, such that the SOC ranged from 42.98% at improved grassland to 54.96% at the cutaway bog (Fig. 3b). In the 0–20 cm, the SOC ranged from 42.31% to 54.73%, with the lowest and highest ends exhibited by improved grassland and the active bog (Fig. 3c). The unimproved grassland (46.62%) exhibited a higher SOC as compared to the improved grassland (42.03) (Fig. 3c).

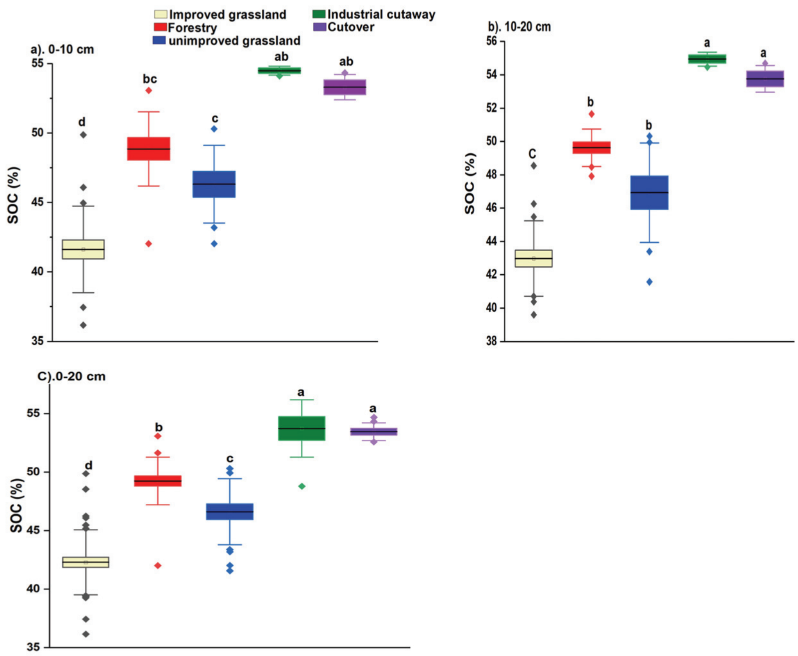

Fig. 3. Effects of land use type on SOC (%). Asterisk marks (lower and upper) in the range represent the 1% and 99% percentiles, respectively. Asterisks outside the range represent outliers. Small rectangular boxes represent mean values. The same letters on the box are not significantly different at p 0.05 using Tukey HSD at the 0.05 significance level.

3.3. Relationship between soil pH and soil organic carbon

The analysis of the collected peat soil samples revealed a significant negative correlation (r > 0.44) between soil pH and SOC content across the two soil depths (0–10 and 10–20 cm) (Fig. 4). This strong negative correlation suggests that as soil pH decreases, the SOC content tends to increase (Fig. 4). A strong negative correlation was observed between SOC content and soil pH, indicating that increased soil pH levels are associated with decreased SOC in temperate peatlands, as reported by other studies (Brunetto et al., 2012; Godsey et al., 2007; McCauley et al., 2009).

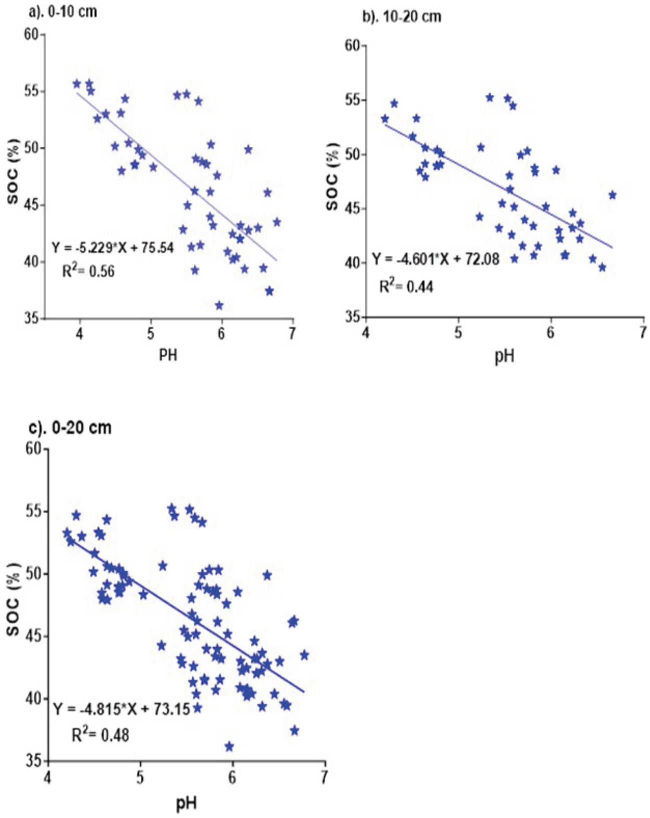

Fig. 4. Relationship between soil pH and soil organic carbon

4. Discussion

In our study, the pH of peat soils under forestry was lower than both the unimproved and improved grassland, which may probably be assigned to the addition of organic matter input through the forest litter material build-up on the peat soil surface and deep rooting system of the tree to release organic acid into the peat soil environment. The pH exhibited by the forest agreed with the study of Agus et al. (2020) as they obtained a low pH (< 4.01) peat soil of secondary forest and attributed their findings to the less intervention or damage and high levels of hydrogen ions derived from the decomposition of organic materials containing lignin while in forest soils in Southwest Germany, the pH range was 3.9 in the organic layer, with a limited natural recovery observed (Jansone, 2020). In the context of grassland management, the regular application of lime and fertilizers, such as manure and NPK fertilizer, emerges as the most common practice, particularly in improved grasslands, to address the inherent natural acidity of peat soil (Berglund, 1996; Crocker and Holford, 1991). This management strategy significantly influences soil pH, with the improved grassland exhibiting a higher pH compared to the unimproved grassland. This is due to the neutralization of soil acidity by lime and the supplementation of essential nutrients by manure and NPK fertilizer (Hart, 1990). The synergistic effect of nutrient availability and pH adjustment fosters an environment conducive to pasture productivity (Dhiman et al., 2019). Cutaway bogs, a result of peat extraction, have the lowest pH among land use types due to the disruption of their natural equilibrium. This is exacerbated by the exposure of mineral layers, increased mineralization, and the production of organic acids during microbial decomposition (Rochefort, 2017). The disturbance from peat extraction also affects the water-holding capacity of the bog, leading to increased leaching of acidic compounds. In contrast, grassland and forestry areas, which may have management practices to mitigate soil acidification, exhibit higher pH levels (Williamson et al., 2017).

Land use change can significantly affect the balance between soil C input and output, ultimately leading to changes in soil organic carbon (SOC) levels. The improved grassland exhibited the least SOC due to their intensive management practices (grazing, fertilizer application, and ploughing etc.), which may alter the natural balance of the organic inputs and outputs in the systems compared to the forestry, implying that natural peatland converted for agriculture purposes lose SOC at a faster rate than the forestry Compton and Boone, 2000; Kasimir-Klemedtsson et al., 1997). Even though grasslands can enhance soil organic carbon (SOC) by releasing root exudates that contain binding agents due to their higher root mass density, which increases physical stability and microbial activity, these mechanisms are not as effective in increasing SOC compared to forestry (Holeplass et al., 2004; Kukal and Bawa, 2014). The tree root biomass and continuous recycling of the litter under the forestry system could explain the higher SOC in the forest peat soil than the grassland peat soil. According to Kukal and Bawa (2014), the differences in the SOC between the grassland and the forestry may be due to the recalcitrant C input from the forest litter falls and the difference in the root architecture of forest trees and grasses. The unimproved grassland exhibited higher soil organic carbon (SOC) levels compared to the improved grassland due to the possible exclusion of certain intensive and frequent management practices (e.g. continuous ploughing, overstocking and fertilizer application etc.), which could contribute to sustainable organic matter turnover, ultimately leading to higher SOC levels (Conant et al., 2001). The cutover bog exhibited the highest SOC than the studied land use due to the minimal disturbance during the peat harvesting for domestic use; hence there are less vegetation cover removal and drainage canals constructed to lower the water table, which could have caused an increase of aerobic decomposition of soil organic matter leading to the loss of the SOC.

5. Conclusions

This study has revealed distinct patterns in soil organic carbon (SOC) content across different land-use types. Notably, both improved and unimproved grasslands exhibited the highest adverse impact on SOC compared to forest, cutover, and cutaway areas. The significantly lower SOC content in the improved grassland can be attributed to intensive management practices such as grazing, fertilizer application, and ploughing, which potentially disrupt the natural balance of organic inputs. The observed SOC levels followed the order: improved grassland < unimproved grassland < forestry < cutaway < cutover. Furthermore, the study highlighted the influence of land management practices on soil pH, with improved grasslands, often subject to lime or other soil amendments, showing the highest pH values. In contrast, cutover areas exhibited the lowest soil pH. This emphasizes the critical role of both land management practices and the presence of vegetation play a crucial role in influencing soil pH and SOC.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analyzed during this study are included in this manuscript.

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