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The Influence of Reclamation Technology and Vegetation Type on Carbon Accumulation and Water Retention of Technogenic Soils in the New Ecosystem Restored on Reclaimed Post-Mine Spoil Heaps

Wpływ technologii rekultywacji i typu pokrywy roślinnej na akumulację węgla i retencję wodną gleb technogenicznych w nowych ekosystemach odtwarzanych na rekultywowanych zwałowiskach pogórniczych

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Summary

Mining for fossil fuels and minerals is a major global economic activity that generates spoil heaps, deep excavations, mine subsidence, and open-cast pits. Despite a growing shift toward renewable energy in the energy mix, spoil heaps still cover over 1% of the Earth's land surface and remain a significant reclamation challenge. Carboniferous rock spoil heaps are widespread in Upper Silesia, forming a dominant feature of the region's coal mining landscape. While these sites pose environmental risks, proper reclamation can transform them into novel ecosystems capable of providing essential services such as carbon sequestration and water retention. The primary objective of this study was to assess the effects of reclamation methods and vegetation types on carbon sequestration and water retention potential in soils of post-mining ecosystems developed on Carboniferous rocks and post-hard coal mine. This was achieved through (i) a critical literature review and (ii) four research studies publish in the international journals. The studies were conducted at the Sośnica hard coal spoil heap in the Upper Silesian Coal Basin, Southern Poland. The review revealed that soil organic carbon (SOC) accumulation in reclaimed mining soils (RMS) was primarily influenced by restoration age, vegetation type, and reclamation technique. Field research demonstrated that topsoil application significantly altered soil properties and organic matter fractions compared to unreclaimed sites. Sites reclaimed with topsoil (RTS) exhibited higher bulk density (BD) and reduced porosity relative to succession on bare-rock (SBR) sites. However, RTS sites achieved substantially higher stocks of SOC and total nitrogen (TN). Furthermore, RTS enhanced the occluded light fraction (C_{oLF}) and mineral-associated carbon fractions (C_{MAF}) in the topsoil (0–10 cm), suggesting improved carbon stabilization in surface layers. In contrast, SBR exhibited higher C_{MAF} in the subsoil (10–20 cm), likely due to the influence of geogenic parent material. Vegetation type further influenced soil properties and SOC dynamics. Grassland and forbland vegetation reduced BD while increasing porosity and capillary water capacity (CWC) in the topsoil compared to woodland. Conversely, woodland displayed lower BD and higher porosity and CWC in the subsoil. Grassland and forbland also enhanced simulated total soil water storage (SWS in mm in 0-20 cm soil layer) relative to woodland. Woodland and forbland communities on reclaimed sites significantly influenced on increasing SOC and TN stocks in the topsoil, although more effectively than natural succession on bare Carboniferous rock. Under woodland, in particular, litter layer accumulated more SOC and TN than soil under grassland and forbland. Additionally, grassland contributed to higher C_{oLF} and C_{MAF} at both soil uppermost layers (depths 0-10 and 10 – 20 cm) compared to forbland and woodland, meanwhile forbland exhibited greater C_{oLF} in 10-20 cm soil layer, than woodland. Therefore, based on the results obtained, it was concluded that grass and forbs vegetation clearly influence carbon stabilization in the developing soil organic matter of the topsoil. Finally, remote sensing and topographic indicators facilitate scalable monitoring of SOC, TN, and SWS, with SOC distribution correlating with the digital terrain model, TN with near-infrared reflectance and NDVI, and SWS with the topographic wetness index and canopy height model, as well. General conclusion demonstrate that grassland and forbland vegetation optimize soil water retention, porosity, and SOC stabilization in uppermost post-mining soils. Moreover, combining topsoil application with woodland cultivation enhances SOC stocks in the litter layer and topsoil, offering a balanced strategy for post-mining soil restoration. The results enable the development of a sustainable reclamation strategy incorporating a mosaic of vegetation types, spontaneous succession, and topsoiling methods. They also permit leaving Carboniferous rocks without mineral soil cover where suitable reclamation substrates are lacking (the so-called soil-less method). In such cases, the additional economic benefits of reclamation could also be significant.

Keywords: coal mining, spoil heap, reclamation, topsoil, succession, soil organic carbon, organic carbon stabilization, water retention, ecosystem services

Streszczenie

Wydobycie paliw kopalnych i minerałów jest jedną z głównych gałęzi światowej gospodarki, która powoduje powstawanie nadpoziomowych zwałowisk i hałd, głębokich wyrobisk kopalń odkrywkowych i osiadania gruntów. Pomimo rosnącego udziału energii odnawialnej w miksie energetycznym, obiekty te nadal pokrywają ponad 1% powierzchni lądowej Ziemi i stanowią poważne wyzwanie dla rekultywacji. Zwałowiska (potocznie zwane hałdami) zbudowane z skał karbońskich i odpadów towarzyszących wydobyciu węgla kamiennego są powszechnie występującymi obiektami na Górnym Śląsku, gdzie stanowią dominujący element krajobrazu regionu górniczego. Chociaż tereny te stanowią zagrożenie dla środowiska, odpowiednia rekultywacja może przekształcić je w nowe ekosystemy zdolne do świadczenia niezbędnych usług, takich jak sekwestracja dwutlenku węgla i retencja wody. Głównym celem niniejszej rozprawy była ocena wpływu metod rekultywacji i rodzajów roślinności na sekwestrację dwutlenku węgla i retencję wodną gleb technogenicznych w nowych ekosystemach odtwarzanych na rekultywowanych zwałowiskach pogórniczych. W skład rozprawy weszły opublikowane prace, w tym (i) praca przeglądowo zawierająca krytyczny przegląd literatury oraz (ii) cztery artykuły badawcze opublikowane na podstawie wyników badań zrealizowanych na zwałowisku odpadów węgla kamiennego Sośnica w Gliwicach na Górnym Śląsku. Artykuł przeglądowy wykazał, że na akumulację węgla organicznego (SOC) w rekultywowanych glebach pogórniczych (oznaczonych z ang. jako RMS) wpływ mają przede wszystkim: wiek obiektu liczony od rozpoczęcia rekultywacji, rodzaj pokrywy roślinnej i technologia rekultywacji. Badania terenowe wykazały, że zastosowanie tzw. metody glebowej z wykorzystaniem wierzchniej warstwy ziemi mineralnej znacząco zmieniło właściwości powstających gleb, w tym szczególnie udział frakcji węgla związanego z glebową materią organiczną w porównaniu z terenami nierekultywowanymi i pozostawionymi sukcesji. Tereny rekultywowane z zastosowaniem metody glebowej z użyciem wierzchniej warstwy ziemi mineralnej (z ang. dla wariantu w pracy przyjęto symbol RTS) wykazywały wyższą gęstość objętościową (BD) i zmniejszoną porowatość w porównaniu z glebami pod zbiorowiskami z sukcesji na terenach niepokrytych warstwą ziemi mineralnej na skałach karbońskich (SBR). Ponadto gleby w kategorii RTS osiągnęły znacznie wyższe zasoby ogólne SOC i azotu całkowitego (TN), a także wykazywały zwiększenie udziału stabilnej (C_{oLF}) i bardzo stabilnej frakcji węgla związanego z minerałami (C_{MAF}) w wierzchniej warstwie gleb (0–10 cm), co sugeruje poprawę stabilizacji węgla w warstwach powierzchniowych. Natomiast w glebach wariantu SBR wykazano wyższą zawartość C_{MAF} w warstwie głębszej (10–20 cm), co prawdopodobnie wynikało jednak z zmieszania z warstwami karbońskiej skały macierzystej zawierającej węgiel geogeniczny. Rodzaj roślinności (typ pokrywy roślinnej) miał dodatkowo wpływ na właściwości gleb i zapas SOC. Roślinność trawiasta i wieloletnia roślinność zielna wpływały na zmniejszenie gęstości objętościowej gleb (BD), zwiększając jednocześnie porowatość i kapilarną pojemność wodną (CWC) w wierzchniej warstwie (0-10 cm) gleb w porównaniu z glebami pod zbiorowiskami drzewiastymi. Natomiast gleby pod zbiorowiskami drzewiastymi wykazywały niższą BD oraz wyższą porowatość i CWC w warstwie nieco głębszej (10-20 cm). Roślinność trawiasta i wieloletnia roślinność zielna wpływały również na zwiększenie potencjalnej zdolności do retencjonowania wody w glebie ogółem (przyjęto jako SWS wyrażone mm/0-20 cm) w porównaniu z glebami pod zbiorowiskami drzewiastymi. Ponadto gleby pod zbiorowiskami trawiastymi oraz roślinnością zielną wprowadzone w ramach rekultywacji wpływały na znaczne zwiększenie ogółem zasobów SOC i TN w wierzchnich (0-10 cm) warstwach gleb, w porównaniu do wpływu zbiorowisk z sukcesji spontanicznej na terenach nierekultywowanych na skałach karbońskich. W szczególności gleby zbiorowisk

drzewiastych charakteryzowały się większym zapasem SOC i TN zgromadzonym dzięki udziałowi warstwy ściółki, w porównaniu do ogólnego zapasu w glebach pod zbiorowiskami trawiastymi i roślinnością zielną. Ponadto w glebach zbiorowisk trawiastych stwierdzono wyższy udział węgla związanego z frakcjami bardziej stabilnymi CoLF i CMAF w obydwu badanych warstwach wierzchnich gleb (0-10 i 10 -20 cm) w porównaniu z glebami zbiorowisk roślinności zielnej i drzewiastej. Podczas gdy pod roślinnością zielną wykazano wyższy udział węgla frakcji CoLF w warstwie głębszej 10-20 cm w porównaniu z glebami zbiorowisk drzewiastych. Podsumowano więc, że na podstawie uzyskanych wyników widać wyraźny wpływ roślinności trawiastej i zielnej wieloletniej na poprawę stabilizacji węgla w tworzącej się glebowej materii organicznej wierzchnich warstw. Zastosowane narzędzia teledetekcyjne i wskaźniki topograficzne pozwoliły opisać model przestrzennej zmienności zapasu SOC, TN i umożliwiły określenie tej zmienności w stosunku do zdolności do retencjonowania wody w glebie. Stwierdzono, że rozkład SOC korelował z cyfrowym modelem terenu, TN z odbiciem w bliskiej podczerwieni i NDVI, a SWS z topograficznym wskaźnikiem wilgotności i modelem wysokości koron drzew. Uzyskane wyniki pokazały, że roślinność trawiasta i wieloletnia roślinność zielna wprowadzone w ramach rekultywacji wpływają na optymalizację retencyjności wodnej, porowatości i stabilizacji SOC w glebach pogórniczych. Z kolei wprowadzanie roślinności drzewiastej w połączeniu z metodą glebową znacząco zwiększa zasoby SOC w warstwie ściółki i wierzchniej warstwie gleb ogółem. Uzyskane wyniki dają możliwość opracowania zrównoważonej strategii rekultywacji z wykorzystaniem mozaiki zbiorowisk, sukcesji spontanicznej i zastosowania metody glebowej. Sformułowane wnioski nie wykluczają także pozostawiania skał karbońskich bez pokrycia ziemią mineralną, w przypadku braku odpowiednich substratów do rekultywacji (tzw. metoda bezglebowa). Wówczas w takich przypadkach nie bez znaczenia będzie także uzyskany dodatkowo efekt ekonomiczny rekultywacji.

Słowa kluczowe: górnictwo węglowe, zwałowiska, rekultywacja, metoda glebowa, sukcesja, glebowy węgiel organiczny, stabilizacja węgla organicznego, retencja wodna, usługi ekosystemowe

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1. Introduction

Natural landscapes globally are undergoing significant changes due to both natural and human activities (Johnson et al., 2017; Seidl et al., 2017). Among human activities, large-scale mining of resources such as coal, lignite, oil shale, and metallic minerals has substantial impacts on ecosystems, affecting their geomorphology, hydrology, and chemistry (Pietrzykowski & Daniels, 2014; Frouz & Vindušková, 2018; Feng et al., 2019). These mining activities result in post-mining landscapes characterized by massive overburden dumps, pollution, CO_2 emissions, and nutrient-poor soils, which hinder ecosystem development (Ahirwal & Maiti, 2017; Pietrzykowski et al., 2021). Additionally, mining can cause off-site pollution through acid mine drainage (Kim & Chon, 2001; Likus-Cieślik et al., 2019).

Despite these challenges, reclamation efforts are essential for restoring these degraded landscapes. Effective reclamation improves soil properties such as organic matter content, microbial activity, soil moisture, and cation exchange capacity, which are critical for vegetation growth and ecosystem recovery (Frouz et al., 2009; Restrepo et al., 2013; Józefowska et al., 2017). Key soil parameters for successful reclamation include soil organic carbon (SOC), total nitrogen (TN), bulk density, water-holding capacity, and porosity (Keller et al., 2013; Pietrzykowski & Daniels, 2014). SOC and TN are particularly important as they indicate soil quality and pedogenesis rates, with SOC enhancing soil structure, porosity, aeration, and water retention (Six & Paustian, 2014; Yan et al., 2020). Revegetation of spoil heaps increases carbon input from litter and biomass, aiding SOC accumulation. Identifying vegetation types and reclamation methods that enhance SOC storage is crucial for mitigating climate change (Chung et al., 2012; Yan et al., 2020). Ultimately, successful reclamation aims to develop long-term sustainable ecosystems with all necessary functions and structures (Pietrzykowski, 2008; Ahirwal & Maiti, 2022).

Bulk density (BD) is crucial for estimating soil carbon storage and assessing soil physical quality (Vereecken et al., 2016). It is closely linked to soil water retention capacity and porosity, which are influenced by soil organic matter (SOM) and texture (Stephens et al., 2003). BD and porosity significantly impact soil water storage (SWS), a vital factor in managing water-stressed ecosystems such as reclaimed mining heaps, where soil water limits plant growth and ecosystem functions (Kuráž, 2001). However, excessive soil compaction negatively affects the physical, chemical, and biological properties of post-mining soils (Rabot et al., 2018). Research shows that reclamation and long-term vegetation restoration significantly reduce BD (Zhao et al., 2013; Cao et al., 2015; Zhang et al., 2015; Lin et al., 2020). Interestingly, the soil under spontaneous succession showed lower BD as effectively as costly reclamation efforts (Cejpek et al., 2013; Zhu et al., 2016; Kołodziej et al., 2017). This finding highlights the need for more research on how different reclamation methods and vegetation types affect BD in post-mining soils.

Vegetation types used in restoration significantly influence carbon cycling by storing carbon in biomass, SOM, and litter. Different vegetation and reclamation methods affect SOC and TN storage due to variations in organic matter input, decomposition rates, and distribution at various soil depths (Frouz, 2008; Zhang et al., 2013; Woś et al., 2021; Singh et al., 2022). Vindušková and Frouz (2013) found lower soil carbon storage in coniferous forests compared to grasslands and deciduous forests on reclaimed mining sites in the Northern Hemisphere. Similarly, Zhang et al. (2020) reported higher SOC and TN accumulation under grasslands than woodlands on China's Loess Plateau. Reclamation with topsoil results in significantly higher SOC accumulation compared to bare rock (Akala & Lal, 2001; Bartuška et al., 2015; Čížková et al., 2018). Pietrzykowski and Krzaklewski (2007) found that SOC and TN accumulation rates were three to five times higher in reclaimed soils than in successional soils, underscoring the importance of reclamation for enhancing soil quality and carbon storage.

The accumulation of SOC is influenced by various SOC fractions, each with different residence times and sensitivities to environmental changes such as climate and land use (Gross & Harrison, 2019). Labile or free light SOC fractions have short residence times and respond quickly, while stable SOC fractions have longer residence times and respond more slowly (Fontaine et al., 2007; Gruba et al., 2015; Soucémarianadin et al., 2018). These differences arise from biological, environmental, and physicochemical factors affecting decomposition (Dynarski et al., 2020). Research indicates that specific reclamation methods and plant species can be more effective in stabilizing SOC in mineral soils (Vesterdal et al., 2013; Gurmesa et al., 2013; Das & Maiti, 2016; Nickels & Prescott, 2021). Understanding the distribution of SOC fractions, including the free light fraction (C_{fLF}), occluded light fraction (C_{oLF}), and highly stable mineral-associated fraction (C_{MAF}), is essential for assessing carbon sources and sinks at post-mining sites. Various studies have explored the effects of reclamation on SOC, focusing on technologies, biotic elements, and abiotic factors (e.g., Akala & Lal, 2001; Pietrzykowski & Krzaklewski, 2007; Frouz & Vindušková, 2018; Yan et al., 2020; Zhang et al., 2020). However, comprehensive analyses of how reclamation methods and vegetation types affect SOC, total nitrogen (TN), and associated soil properties are still lacking.

Carboniferous rock spoil heaps, prevalent in coal mining regions like Upper Silesia, present significant environmental challenges but also opportunities for enhancing regional climate resilience through ecosystem services like carbon sequestration and water retention. Optimizing reclamation methods for these spoil heaps is crucial for climate regulation and mitigating mining impacts (Zedler & Kercher, 2005; Conti & Díaz, 2013). Therefore, understanding the interactions between reclamation technology, vegetation cover, carbon sequestration, and water retention are vital for restoring and developing ecosystem services. Comprehensive research in this area is critical to address the rising carbon dioxide and to enhance water retention. Identifying effective reclamation technologies and vegetation types can enhance both carbon sequestration and water retention in the context of climate change.

The PhD thesis is completed with a series of published works, which provides a comprehensive analysis of the effects of reclamation methods and vegetation on carbon accumulation and water retention in technogenic soils on reclaimed post-mine spoil heaps. The findings of the study were published in the following papers:

Publication No. 1. A critical review was conducted to summarize the impact of new ecosystems developed on post-mining sites on SOC accumulation and to identify the key factors affecting the amount of carbon accumulating on reclaimed post-mining soils: Misebo, *A. M., Pietrzykowski, M., & Woś, B. (2022). Soil carbon sequestration in novel ecosystems at post-mine sites—a new insight into the determination of key factors in the restoration of terrestrial ecosystems. Forests, 13(1), 63. https://doi.org/10.3390/f13010063. (Pnt. MNiSW: 100; IF: 2.9);*

Publication No. 2. The research was conducted to determine the effect of reclamation scenario and vegetation types on physical parameters and water storage of soils developed on carboniferous mine spoil heap: *Misebo, A. M., Szostak, M., Sierka, E., Pietrzykowski, M., & Woś, B. (2023). The interactive effect of reclamation scenario and vegetation types on physical parameters of soils developed on carboniferous mine spoil heap. Land Degradation & Development, 34(12), 3593–3605. https://doi.org/10.1002/ldr.4705. (Pnt. MNiSW: 200; IF: 3.6);*

Publication No. 3. The purpose of the paper was to evaluate the influence of vegetation types and reclamation treatments on soil organic carbon and nitrogen in developing soils on a spoil heap of carboniferous rocks: *Misebo, A. M., Sierka, E., Woś, B., & Pietrzykowski, M (2024). Soil organic carbon and nitrogen in developing soils on a spoil heap of carboniferous rocks were influenced by vegetation types and reclamation treatments. Land Degradation & Development, 35(16), 4830–4840. https://doi.org/10.1002/ldr.5260,(Pnt. MNiSW: 200; IF: 3.6);*

Publication No. 4. The aim of the study was to find out the effect of reclamation method and vegetation types on labile and stable soil organic carbon fractions in spoil heaps of coal mining waste: *Misebo, A. M., Woś, B, Gruba P., & Pietrzykowski, M (2025). Reclamation and vegetation effects on labile and stable soil organic carbon fractions in spoil heaps of coal mining waste. Pedosphere. https://doi.org/10.1016/j.pedsph.2025.04.004, (Pnt. MNiSW: 70; IF: 5.2);*

Publication No. 5. The objective of the study was for spatial estimation of soil organic carbon, total nitrogen, and soil water storage in reclaimed post-mining site based on remote sensing data. *Misebo, A. M., Hawryło, P., Szostak, M., & Pietrzykowski, M. (2024). Spatial estimation of soil organic carbon, total nitrogen, and soil water storage in reclaimed post-mining site based on remote sensing data. Ecological Indicators, 165 (2024),112228, https://doi.org/10.1016/j.ecolind.2024.112228, (Pnt. MNiSW: 200; IF: 7.0).*

This dissertation is in frame of OPUS 20 project, No. 2020/39/B/ST10/00862, titled "Effects of Brownfield Rehabilitation Methods and Revegetation Scenarios on Functional Diversity, Carbon Sequestration, and Water Retention in Novel Ecosystems" (2021–2024), funded by the National Science Centre (NCN) and led by prof. Marcin Pietrzykowski. In the research and implementation of the dissertation, I played a leading role in the formulation of the research objectives, conception, implementation of the study and conduct of the experiment on selected study sites connected with my PhD thesis, and of course interpretation of the results, and preparation of the manuscripts (see the appendix "Author's copyright Statements" for the percentages and contributions).

2. Aim and hypotheses of the study

The main purpose of the dissertation was to investigate the impact of the applied spoil heap reclamation methods and the type of vegetation cover (introduced and spontaneous succession) on carbon sequestration and water retention in the novel ecosystem of a hard coal post-mining spoil heap.

The dissertation formulated the following research hypotheses:

H_1: Carbon sequestration and water retention in novel ecosystems on post-mine sites are functions of reclamation technology and vegetation cover type.

H_2: Reclamation treatments may enhance carbon sequestration and water retention potential on post-mine spoil heaps compared to natural succession.

H_3: The levels of SOC fractions are strongly correlated with vegetation type and reclamation method.

3. Description of the study area and experimental design

The study was conducted in southern Poland at the Sośnica hard coal post-mining spoil heap (50º 16' 22" N, 18º 44' 43" E) in Gliwice and Zabrze, Upper Silesian Coal Basin (Fig. 1). The site has an average annual temperature of 8.5°C and a mean annual precipitation of 727 mm. Hard coal was mined at the site for more than 250 years (Kompała-Bąba et al., 2021). The spoil heap deposits comprise carboniferous rocks, primarily shale, sandstone, and conglomerates. They have poor water retention, low SOM content and nutrient availability, and high geogenic carbon (fossil) content (Cabała et al., 2004). Reclamation activities include forming and leveling the surface, applying topsoil, and cultivating various tree species, forbs, and grasses were implemented. Partly, a succession of different vegetation types occurs on reclaimed topsoil and unreclaimed bare rock (Kompała-Bąba et al., 2019). Age of all sites ranged from 20 to 25 years. The most common vegetation in the study area was *Arrhenatherum elatius, Chamaenerion palustre, Calamagrostis epigejos, Festuca rubra, Solidago gigantea, Daucus carota, Melilotus alba, Populus tremula, Pinus sylvestris, Betula pendula, Alnus glutinosa, Salix alba, Robinia pseudoacacia, Padus serotina, Populus hybrids, Populus nigra,* and *Lupinus polyphyllus,* which is an alien plant.

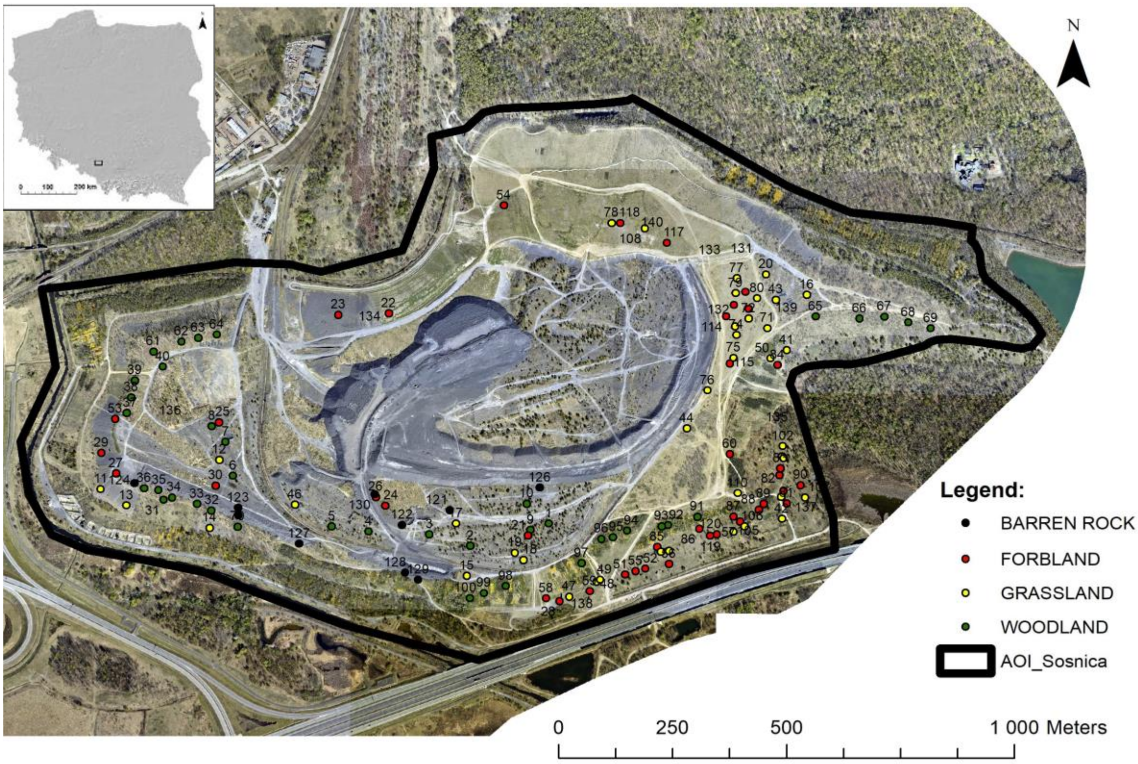

Figure 1: Map of the study site: a general map of Poland and the AOI (area of interest) Sośnica.

A reconnaissance survey was carried out to gain a thorough understanding of the novel ecosystem's reclamation technology and vegetation types. The fragments of the investigated spoil heap where the research plots were located were then classified into 9 variants of the experiment based on reclamation technologies and vegetation types using land monitoring, documentation, and remote sensing data (Fig. 2).

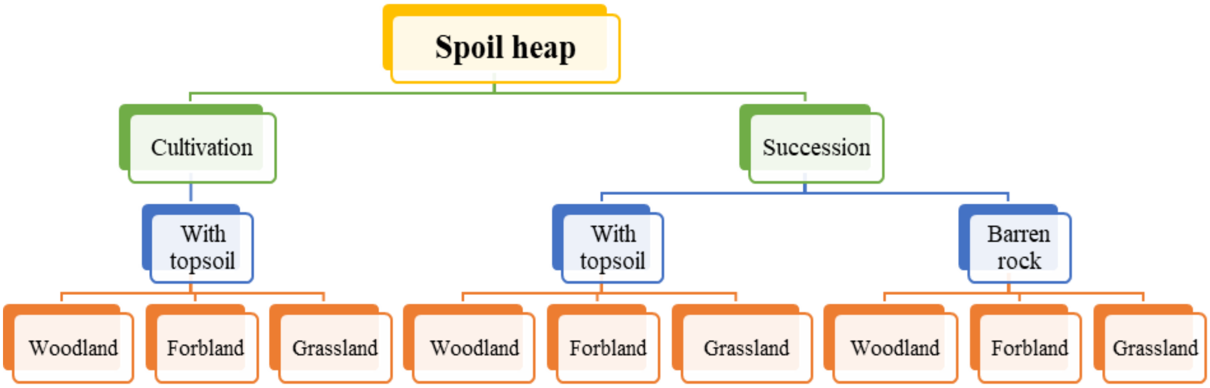

Figure 2: Figure presenting nine experimental variant indicating reclamation scenarios and types of vegetation

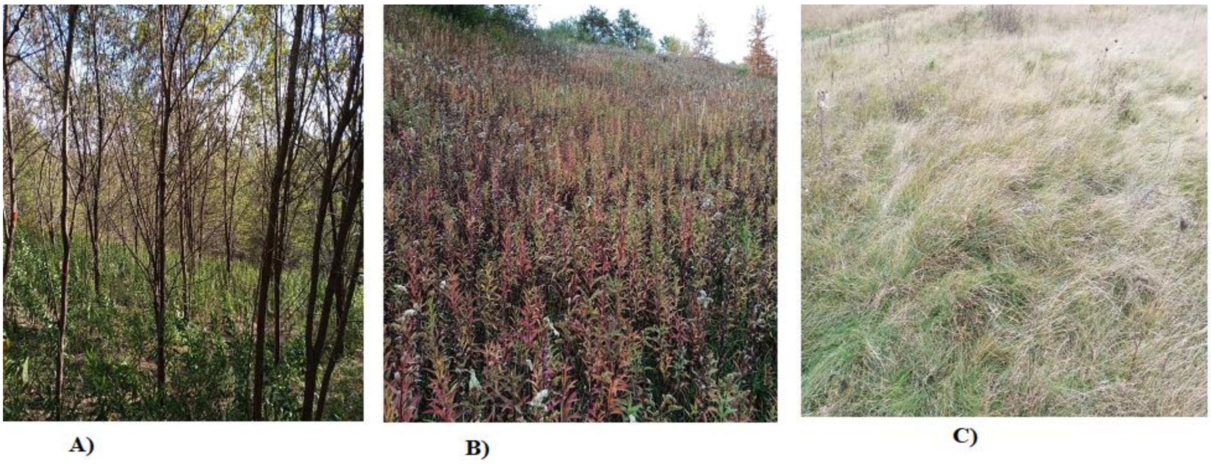

Figure 3: Selected vegetation types developed on the mining heap; A ─ woodland with Robinia pseudoacacia; B ─forbland with Solidago gigantea; C ─ grassland with Festuca rubra (photo by A.M. Misebo)

The soil sample for this study was collected from both active reclamation plots, where the introduction of vegetation (including grasses, shrubs, and trees) occurred through reclamation (topsoiling); and passive reclamation plots, characterized by the natural succession of grasses, shrubs, and trees, with and without applied topsoil. Totally, 130 research plots with 10 × 10 m were randomly established on the identified experimental patches of the spoil heap. Out of 130 research plots, 60 were established on spontaneous succession (forbland, grassland, and woodlands from succession under bare rock and topsoil application) with 10 replications in each variant, whereas 60 were established on active reclamation (topsoil application and cultivation) based on dominant species and large area coverage; on forbland 10 replications each on L. *polyphyllus* and *Melilotus alba*, on grassland 10 replications each on *Festuca ruba* and *Arrhenatherum elatius* and on woodlands 10 replications on *Robinia pseudoacacia* and 10 replications on a mixture of different species, such as *Betula pendula*, *Alnus glutinosa*, and *Larix decidua*. 10 replicates were established on the barren rock to account for the carbon correction due to geogenic carbon derived from coal (Fig. 1).

Samples were collected from the litter layer (Oi+Oe), uppermost topsoil (0–10 cm) and subsoil from each plot in October 2021. The litter layer (Oi+Oe) samples were collected from five 20 × 20 cm squares in each plot. A composite soil sample (weighing approximately 1.0kg when fresh) for each plot was collected from five subsamples (4 points at the corners and one in the middle of each plot). To determine bulk density, porosity, capillary water capacity, and soil water storage samples of the intact structure were collected into 100cm^3 cylinders from the middle of each plot at both depths. The fresh weight of the litter layer was measured with an electronic scale and oven-dried to remove moisture before the weight of the dry mass was calculated, then ground for chemical analysis. The collected composite soil samples were air-dried, sieved with 2-mm mesh, and subjected to analyses for selected physicochemical properties.

4. Methodology and Results

4.1. Soil carbon sequestration in novel ecosystems at post-mine sites: key factors for ecosystem restoration

The key factors that affect the storage of soil organic carbon in the restoration of terrestrial ecosystem at post-mine site was presented in the paper *Misebo et al.,2022.* The review was conducted by searching for relevant research studies from different regions of the world on soil organic carbon sequestration in novel ecosystems at post-mining sites.

The review finding indicate that the accumulation of SOC on reclaimed sites is strongly influenced by factors such as stand age, vegetation type, pre-restoration treatments, restoration strategies, and climatic conditions. Studies on chronosequence reveal that carbon stocks generally increase as restoration ages, primarily due to the continuous addition of organic carbon to the soil. As reclaimed sites ages, diverse vegetation types, including trees, shrubs, and grasses, add organic matter through litterfall, branches, and root systems, which in turn promotes soil development and SOC accumulation in post-mining areas.

The effectiveness of different vegetation types in SOC accumulation varies significantly, apparently due to leaf litter decomposition rate and biomass composition. Leguminous vegetation and grasses are often highly effective at enhancing SOC accumulation. In forest ecosystems, over 80% of carbon is stored in tree biomass, whereas in grasslands, the majority of carbon is sequestered directly in the soil. Selecting suitable tree species is thus essential for enhancing SOC in reclaimed mine sites, especially given the challenging soil conditions in these areas, which often include high rock fragment content, low water retention, low pH, high bulk density, low microbial activity, and limited nutrient content. Factors such as soil moisture, biomass production, and organic matter contributions from vegetation further improve soil properties, support plant growth, and enhance carbon storage. Furthermore, studies suggest that for optimal SOC accumulation in the temperate zone of the Northern Hemisphere, grasses are best suited to warmer, conifers to colder, and deciduous trees to areas with intermediate temperatures, given the significant influence of temperature on vegetation types.

Reclamation methods like topsoil application, hydroseeding, and adding topsoil with short-lived annual seeds improve soil's physical and chemical properties, fostering favorable conditions for plant establishment and SOC accumulation. The selection of reclamation methods is critical for maximizing SOC. For example, a study in India showed that topsoiling in a reclaimed coal mine area resulted in a five-fold increase in SOC, achieving 9.03 Mg C ha^{-1} over five years, compared to unreclaimed sites. In Poland, one year of applying lupine green manure was shown to increase SOC by 13.55 Mg ha^{-1}. Similarly, in Canada, using biosolid amendments in mine reclamation significantly boosted SOC sequestration, achieving an average increase of 6.3 Mg ha^{-1} yr^{-1} compared to only 0.72 Mg ha^{-1} yr^{-1} in sites without amendments.

Thus, these results conclude that strategic reclamation methods, vegetation selection, and restoration age are critical to optimizing SOC accumulation in reclaimed post-mining sites, thereby supporting sustainable ecosystem recovery and enhancing carbon sequestration efforts in reclaimed mining sites (RMS).

4.2. The impact of reclamation methods and vegetation types on soil physical properties and water retention

The effect of reclamation methods and vegetation types on physical parameters for soil water retention and water storage on carboniferous mine spoil heap has been presented in the paper *Misebo et al., 2023*. For the paper, data from 120 research plots were analyzed, including nine variants from both the topsoil (0-10 cm) and the subsoil (10-20 cm). Soil samples were analyzed for texture, bulk density (BD, g/cm^3), capillary water holding capacity (CWC%), porosity, and soil water storage (SWS). These parameters were calculated using equations from Sumner (2010) and Zhang & Shangguan (2016). To assess the influence of reclamation technologies and vegetation types on the examined physical properties (BD, porosity, CWC, and SWS), statistical analyses were performed using Statistica 12.0 Software (StatSoft, Inc. 2014). Means, standard deviations, ANOVA, and Tukey's HSD were computed. All means were considered significantly different at $p < 0.05$.

It was found that the use of topsoil in reclamation significantly affected soil texture and physical properties. Sites reclaimed with topsoil showed a higher silt content (43-48%) compared to those without it (31-34%), where sand and clay levels were higher.

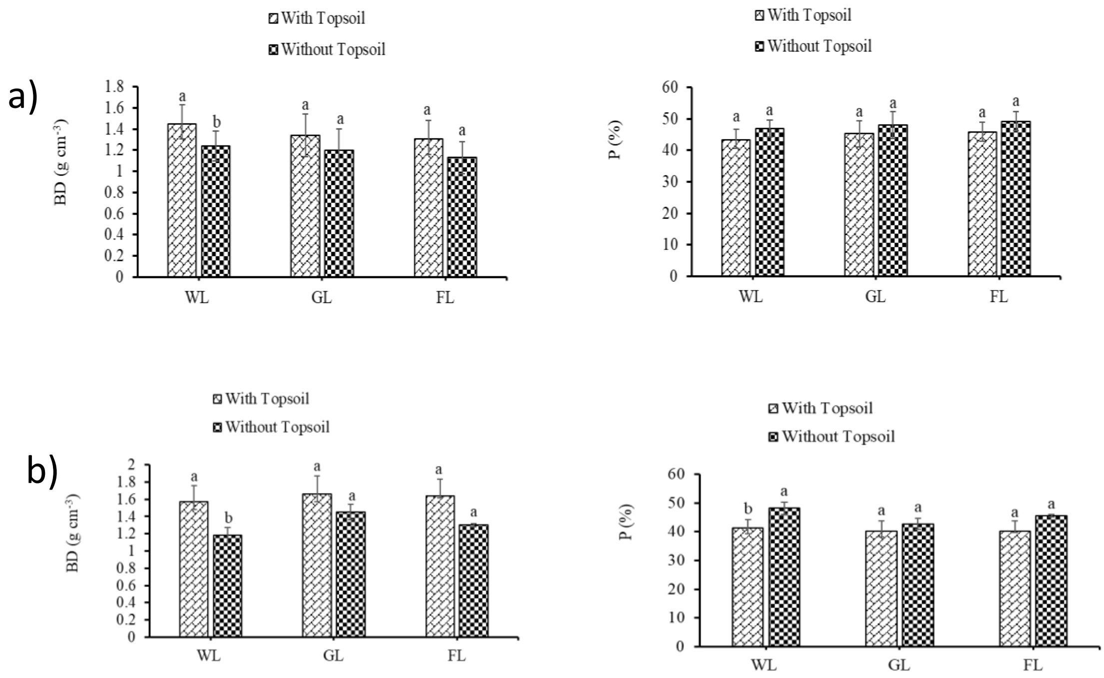

Figure 4: The effect of reclamation (with topsoiling and without topsoiling) on BD and porosity (P) under vegetation types at 0-10 cm (a) and 10-20 cm (b); WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a, b) are significantly different (at $p < 0.05$).

Topsoil application also impacted bulk density (BD) and porosity, specifically increasing BD in woodland areas at both soil depths (0-10 cm and 10-20 cm) and reducing porosity in the 10-20 cm layer (Fig. 4). Spatial patterns in BD also emerged, with values rising in specific directions across the site, indicating a systematic impact of reclamation on soil compaction and texture. As a method for vegetation establishment on mining heaps, spontaneous succession proved effective mainly at the 10-20 cm soil depth in woodland areas, where it significantly lowered BD and increased porosity, improving soil structure. However, at the 0-10 cm depth and in terms of soil water content (CWC) at both depths, succession showed no notable differences compared to cultivation across all vegetation types.

Vegetation types had a substantial impact on BD, porosity, and soil water storage (SWS). Forbland had lower BD than woodland in the 0-10 cm depth, while woodland had a lower BD than grassland and forbland at the 10-20 cm depth. Porosity was highest under forbland at 0-10 cm but was higher under woodland than under grassland and forbland at 10-20 cm. Vegetation also affected the soil's capacity to retain water; grassland and forbland had higher CWC than woodland at the topsoil layer (Fig. 5).

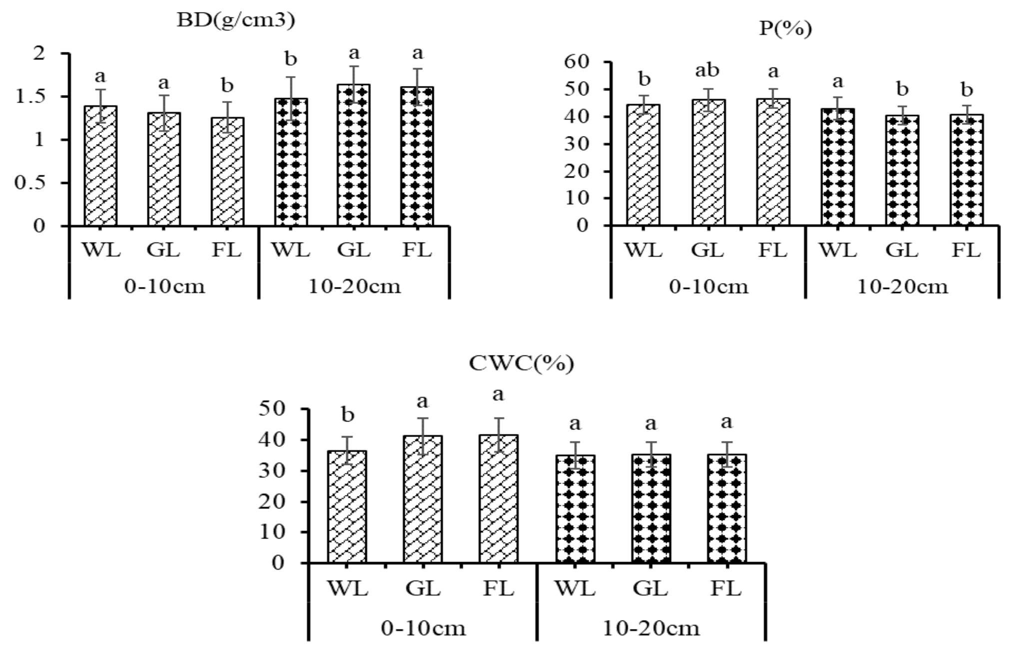

Figure 5: The effect of vegetation types on BD, porosity (P), and CWC of the reclaimed novel ecosystem soil at 0-10 cm (at left) and 10-20 cm (at right) depths; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a, b) are significantly different (at $p < 0.05$).

SWS also varied significantly across vegetation types, with grassland and forbland showing greater SWS than woodland at both soil depths (Fig. 6). These vegetation effects on soil properties were also spatially patterned, with SWS higher in the east and lower in the west, aligned with the distribution of grassland and forbland, indicating vegetation's role in enhancing water retention across the site.

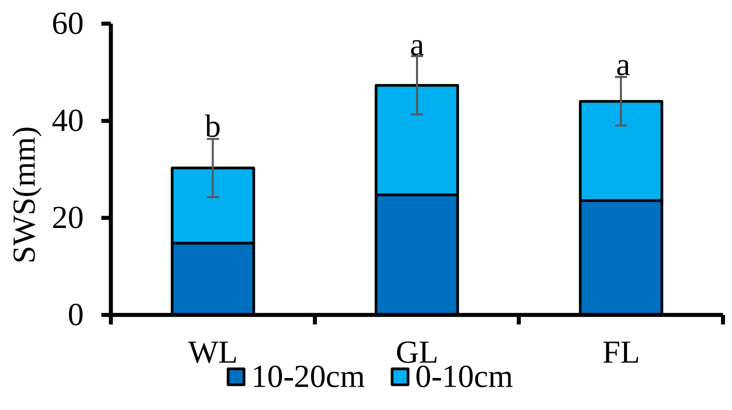

Figure 6: SWS under vegetation types along depths; WL- woodland, GL-grassland, and FL-forbland. The different letters between different vegetation types indicate significant differences at $p<0.05$.

The findings conclude that reclamation methods and vegetation types are essential for improving key physical soil properties necessary for effective ecosystem services. Spontaneous succession had similar effects on BD, porosity and CWC as cultivation. Given the high costs and extensive earthworks associated with topsoiling and active reclamation, incorporating passive restoration through spontaneous succession is advisable. Grassland showed the highest SWS, followed by forbland, while woodland had the lowest. To enhance water-related soil properties and water storage on post-mining heaps, initial revegetation with grasses and forbs should be followed by tree planting. Overall, passive restoration through spontaneous succession and using grasses and forbs is recommended for its cost-effectiveness and comparable benefits to BD, porosity, CWC, and SWS.

4.3. The effect of reclamation and vegetation types on soil organic carbon stock

The results of the effect of vegetation type and reclamation treatment on soil organic carbon and nitrogen in a carboniferous spoil heap are presented in the paper *Misebo et al., 2024.* For this paper, data from 130 research plots was used. Limited soil development on bare overburden and unweathered rock fragments results in significant geogenic carbon presence in the parent material. To address this, samples collected from litter layer (Oi+Oe) and soil samples from the topsoil layer (0-10 cm) were used to minimize its impact. The data collected from 10 plots established on bare rock was used to correct for the fossil organic carbon present in the dumped spoil material under spontaneous succession on bare rock without applied topsoil (Frouz et al., 2009; Reintam, 2004). Soil samples were analyzed for carbon and nitrogen in the litter layer (Oi+Oe) and the top mineral layer (0-10cm), and soil organic carbon (SOC) and total nitrogen (TN) stocks were calculated for each layer. A two-way ANOVA assessed the effects of vegetation types and reclamation technologies on SOC, TN, and C:N stoichiometry. Means, standard deviations, and Tukey's HSD were calculated after verifying data normality (Kolmogorov–Smirnov test). Analyses were performed using Statistica 13.3 (StatSoft, Inc., 2014), with significance set at $p < 0.05$.

It was found that reclamation, primarily through the application of topsoil, significantly influenced soil organic carbon (SOC) and total nitrogen (TN) stocks, particularly at the 0-10 cm soil depth. The addition of topsoil led to notably higher SOC and TN stocks at this depth across all vegetation types. However, the effect varied depending on whether succession or cultivation was used as the reclamation approach. In woodland, topsoil application combined with cultivation increased SOC and TN stocks in the 0-10 cm layer compared to succession on topsoil or bare rock. For forbland and grassland, both succession and cultivation on topsoil yielded significantly higher TN stocks than succession on bare rock (Fig. 7, 8, & 9).

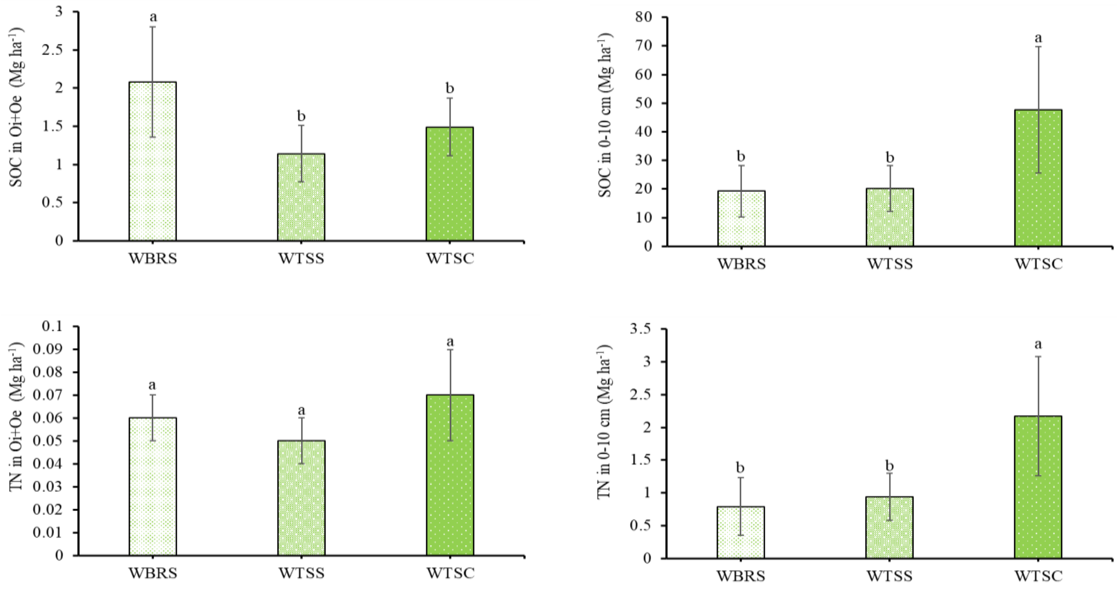

Figure 7: The effect of reclamation techniques on SOC and TN stocks; WBRS: woodland on bare rock succession, WTSS: woodland on topsoil succession, WTSC: woodland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$.

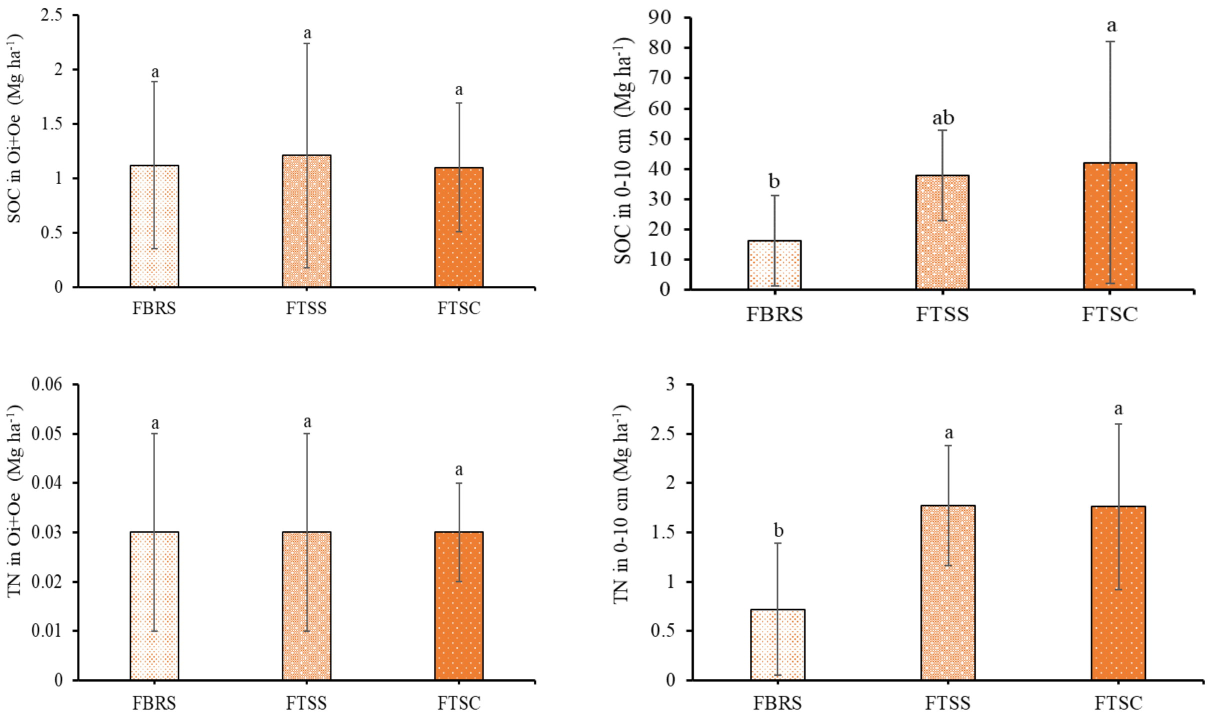

Figure 8: The effect of reclamation techniques on SOC and TN stocks; FBRS: forbland on bare rock succession, FTSS: forbland on topsoil succession, FTSC: forbland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$.

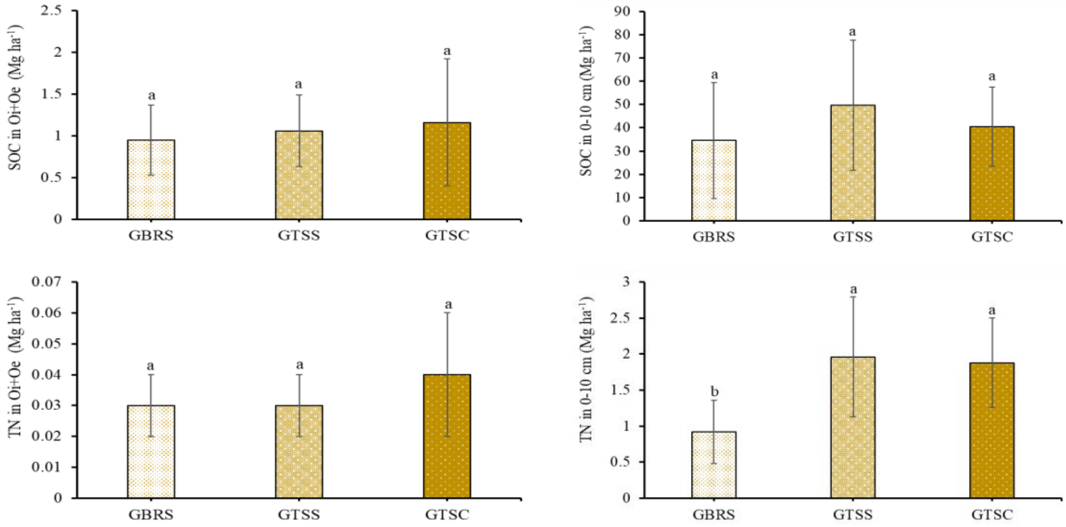

Figure 9: The effect of reclamation techniques on SOC and TN stocks; GBRS: grassland on bare rock succession, GTSS: grassland on topsoil succession, GTSC: grassland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$.

Additionally, topsoil application and cultivation generally reduced the carbon-to-nitrogen (C:N) ratio in the topsoil layer compared to non-reclaimed sites, suggesting improved nutrient availability (Table 1).

Table 1: Carbon and nitrogen stoichiometry in soils under the influence of different vegetation and reclamation

Reclamation	**Vegetation**	**C:N**	
		Oi+Oe	**A horizon**
TSC	Woodland	26±9b[1]	25±11a
	Forbland	47±13a	21±8a
	Grassland	44±9a	21±6a
TSS	Woodland	33±6b	21±6a
	Forbland	81±33a	21±3a
	Grassland	51±8ab	25±6a
BRS	Woodland	38±5a	37±3a
	Forbland	54±14a	36±3a
	Grassland	46±7a	39±5a

[1] means followed by different lowercase (a, b) are significantly different (at $p < 0.05$); TSC: topsoil cultivation; TSS: topsoil succession; BRS: bare rock succession.

Vegetation type played a critical role in SOC and TN dynamics, especially in the litter layer. Woodland soils exhibited higher SOC and TN stocks in the litter layer compared to soils under forbland and grassland, highlighting the role of woody vegetation in contributing organic matter and nutrients to the soil surface (Fig. 10). Additionally, woodland maintained lower C:N ratios in the litter layer, indicating faster nutrient cycling compared to the higher C:N ratios observed in the litter layers of forbland and grassland (Table 1). In the 0-10 cm soil depth, vegetation type showed less impact on SOC and TN compared to reclamation methods; however, succession on bare rock under woodland showed a unique response, with higher SOC stocks in the litter layer compared to succession or cultivation on applied topsoil. For all vegetation types, succession on bare rock yielded higher C:N ratios in the topsoil than vegetation on reclaimed sites, reflecting the slower decomposition and nutrient cycling in bare rock succession compared to reclaimed soils with topsoil. The correlation analysis revealed that pH was positively correlated with SOC and TN. Clay had a positive correlation with TN, while sand had a negative correlation with TN.

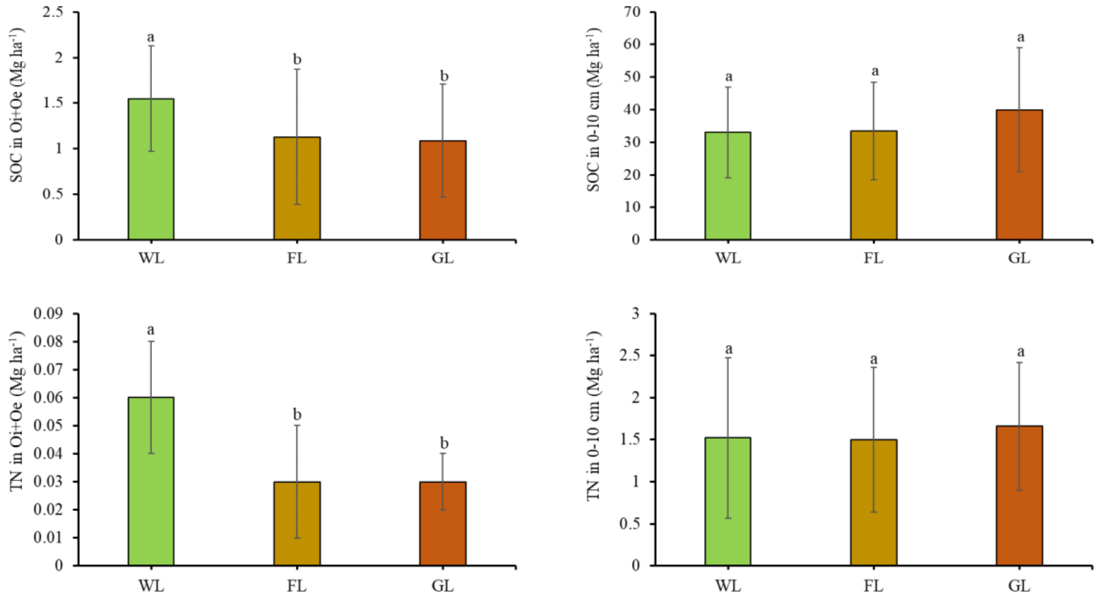

Figure 10: The effect of vegetation type on SOC and TN stocks; WL: woodland, FL: forbland, GL: grassland; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$

The results obtained concludes that reclamation with topsoil led to higher SOC storage. Additionally, the combination of topsoil application and cultivation (active restoration) resulted in higher SOC stocks under woodland and forbland compared to succession on bare rock (passive restoration). In contrast, grassland maintained similar SOC stocks regardless of topsoil application. Woodland exhibited higher SOC stocks in the litter layer compared to forbland and grassland. Therefore, for optimal SOC storage, the most effective reclamation strategy is woodland vegetation with topsoil application and cultivation. However, in areas where topsoil is unavailable and costly for reclamation, grasses are effective in enhancing SOC stocks in post-mining heaps.

4.4. Effects of reclamation method and vegetation types on labile and stable soil organic carbon fractions

The results of the effect of vegetation type and reclamation treatment on labile and stable soil organic carbon fractions in spoil heaps of coal mining waste are presented in the paper *Misebo et al., 2025.* Soil sample data from 54 plots, representing functional plant groupings, was selected from the total sample plots for this detailed fractional analysis. Soil samples were analyzed for SOM fractions such as free light fraction (fLF), occluded light fraction (oLF) and mineral-associated fraction (MAF), and the carbon content of each fraction (fLF, oLF and MAF) was determined using a LECO TruMac® CNS analyzer (von Lützow et al., 2007). Two-way analysis of variance (ANOVA) was used to investigate the effects of vegetation type and reclamation technology on the SOC fraction. The mean, standard deviation, and Tukey's honestly significant difference (HSD) were calculated. Statistica 13.3 (StatSoft, Inc. 2014) software was used for statistical analyses. All means were considered different when $p < 0.05$. It was found that the reclamation had a significant effect on the free light fraction (C_{fLF}), occluded light fraction (C_{oLF}), and mineral-associated fraction (C_{MAF}) of soil carbon. Vegetation type affected C_{oLF} at the 0-10 cm depth, while at the 10-20 cm depth, it impacted C_{fLF}, C_{oLF}, and C_{MAF}. At the 0-10 cm level, soils under succession on barren rock (SBR) showed the highest C_{fLF}, surpassing those under succession and cultivation on topsoil. C_{oLF} values were significantly higher in topsoiled areas than barren rock at both depths. C_{MAF} was most abundant at the 0-10 cm depth with topsoiling but highest under SBR at the 10-20 cm depth compared to succession on topsoil (STS) and cultivation on topsoil (CTS, Fig. 11).

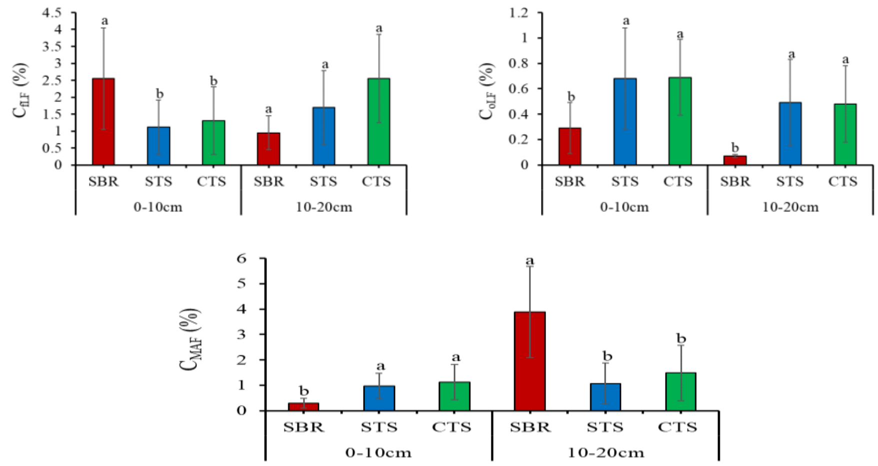

Figure 11: The effect reclamation methods on CfLF: free light fraction of carbon; CoLF: occluded light fraction of carbon; and CMAF: mineral-associated fraction of carbon. SBR: succession on bare rock; STS: succession on topsoiling; CTS: cultivation on topsoiling.

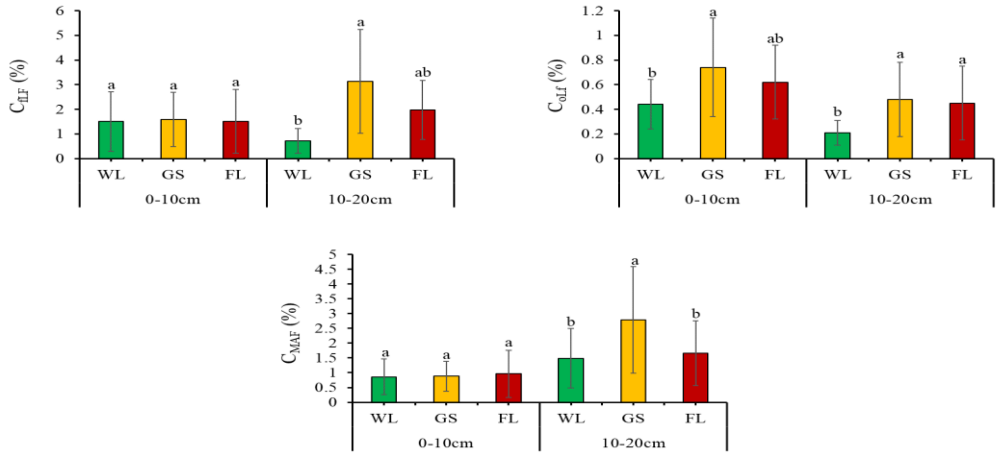

Figure 12: The effect vegetation type on CfLF: free light fraction of carbon; CoLF: occluded light fraction of carbon; and CMAF: mineral-associated fraction of carbon. WL: woodland; GS: grassland; FL: forbland.

Restoration with different vegetation types led to notable differences in soil organic carbon (SOC) fractions. At the 0-10 cm depth, grassland (GL) had significantly higher C_{oLF} than woodland (WL). At the 10-20 cm depth, GL showed significantly higher levels of C_{fLF}, C_{oLF}, and C_{MAF} than WL and had a greater amount of C_{MAF} compared to forbland (FL). Additionally, FL exhibited the highest C_{oLF} when compared to WL (Fig. 12). Among the SOC fractions, C_{fLF} had the largest proportion of the SOC pool at the 0-10 cm depth under all reclamation methods, indicating that reclamation and revegetation of post-mining sites contributed significantly to recent soil organic carbon (C_{fLF}) in the upper soil layer, while deeper soils (10-20 cm) under SBR had higher C_{MAF}. At the control site (bare overburden without vegetation), C_{MAF} dominated at both depths (Fig. 13).

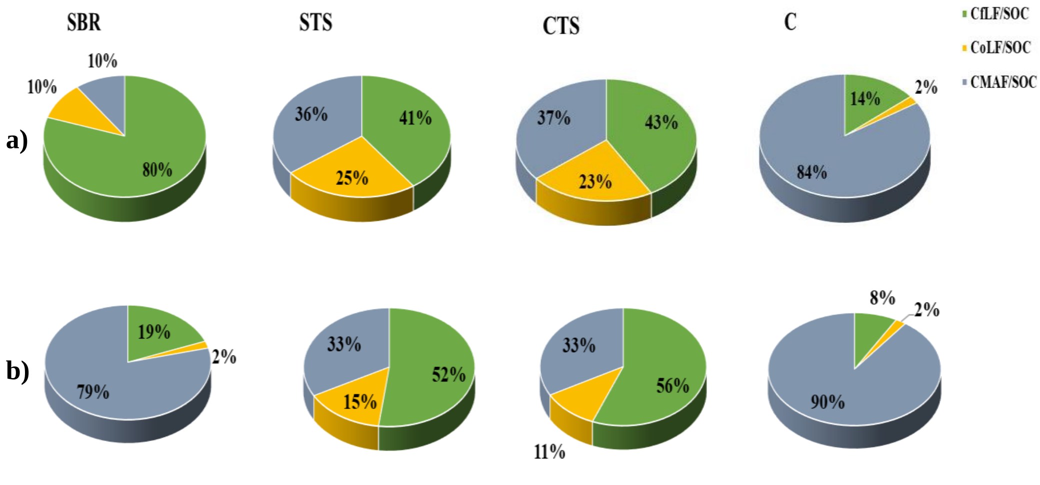

Figure 13: Share of SOC fraction in the SOC pool in a) 0-10cm, and b) 10-20cm depths. SBR: succession on bare rock; STS: succession on applied topsoil; CTS: cultivation on applied topsoil, C: control

C_{fLF} was positively correlated with sand, nitrogen (Nt), sulfur (St), and magnesium (Mg^{2+}), and negatively correlated with clay, bulk density (BD), pH, and calcium (Ca^{2+}). C_{oLF} positively correlated with pH, Nt, and potassium (K^+) and negatively with BD and Mg^{2+}. C_{MAF} showed positive correlations with pH, Nt, Ca^{2+}, and K^+.
The result concluding the combined influence of reclamation method and vegetation functional groups on SOC fractions at postmining sites. Reclaimed sites with topsoil exhibited a significant increase in C_{oLF}, indicating that enhanced humification is critical for maintaining stable SOC pools responsible for continuous carbon sequestration. Furthermore, the study conclude that grasslands played an important role in influencing SOC fractions, contributing to the stabilization of soil organic carbon at the studied postmining site. The findings recommend topsoiling and revegetation of post-mining sites particularly with grasses to increase recent SOM accumulation, resulting in a greater proportion of the labile fraction existing in reclaimed post-mining sites.

4.5. Spatial estimation of soil organic carbon, total nitrogen, and soil water storage

The possibility of using GIS on the spatial estimation of soil organic carbon, total nitrogen, and soil water storage in reclaimed post-mining site is presented in the paper *Misebo et al., 2024.* To carry out the research, data collected in previous studies to estimate SWS (Misebo et al., 2023), and SOC and TN (Misebo et al., 2024), used as reference points for this study. To reach the research goal different types of datasets were used, including: 1) aerial orthophotomaps: year of acquisition: 2019; RGB and CIR (Color Infrared) compositions; source: Main Office of Geodesy and Cartography, Poland (source: geoportal.gov.pl); 2) PlanetScope satellite imagery (Planet) – acquisition date: 18.06.2021; four spectral bands: Blue, Green, Red, and NIR (near infrared). The constellation includes more than 150 nanosatellites and provides a unique dataset of Earth-based observations (Szostak et. al 2021); and 3) Airborne Laser Scanning (ALS) point clouds – a year of acquisition: 2019; density: 12 pts/m^2; source: Main Office of Geodesy and Cartography, Poland, (source: geoportal.gov.pl).
For the development of predictive models, the ten potential explanatory variables were used. The Generalized Additive Model (GAM) approach was used for the development of predictive models for SOC, SWS, and TN. The models were developed using the mgcv package for R. To visualize the spatial distribution of the analyzed variables the prediction in a 10 m square grid was performed (Fig. 17).

The result indicates that SOC storage was mainly influenced by digital terrain model (DTM) and spectral reflectance in Blue band. A slight influence was also observed for Aspect. Based on the analysis of the partial effect plots, it can be observed that among the variables selected by the model, DTM exerts the greatest influence on SOC, causing variations in SOC storage ranging from -8 to 18, assuming other variables are held at their mean values. For elevations up to around 250 m a.s.l. the elevation caused decrease in SOC, while for elevation above 250 m a.s.l. there was slight increase of SOC. Slightly higher SOC values were observed on northern aspects, while lower values were observed on southern aspects. An increase in spectral reflectance in blue band values until reaching approx. 0.6 caused decrease of SOC storage; thereafter, very wide confidence intervals for effect of blue band were observed (Fig. 14).

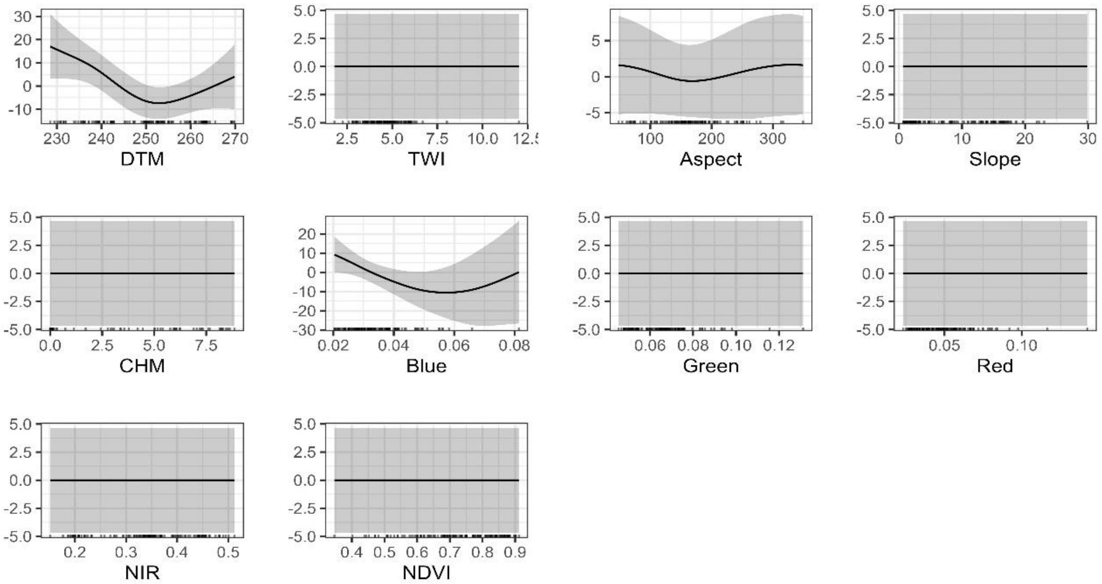

Figure 14: Partial effect plots showing the influence of explanatory variables on SOC in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

Topographic wetness index (TWI), Aspect, canopy height model (CHM), blue, and near infrared (NIR) all had an impact on SWS. Higher values of TWI and NIR corresponded to an increase in SWS, while higher values of blue were associated with a decrease in SWS. Higher SWS values were observed on northern aspects, while lower values were observed on southern aspects. The increased SWS was seen under a lower CHM (linked to grasses); it then decreased until CHM reached 2.5 m, after which it began to rise again. Among the variables, TWI and CHM exert a greater influence, causing variations in SWS ranging from -2 to 5.1 and -6 to 2, respectively, when other variables are held at their mean values (Fig. 15). TN affected by DTM, CHM, blue, green, NIR, and normalized difference vegetation index (NDVI). There is an inverse relationship between TN and both Blue and NDVI. TN exhibits a significant increase with higher values of CHM and NIR. Response plots demonstrate TN's fluctuation with DTM; there is a slight increase initially, followed by a decrease after 235 m, and then a subsequent increase above 250 m. Among the variables, DTM, NIR, and NDVI exert a greater influence when other variables are held at their mean values (Fig. 16).

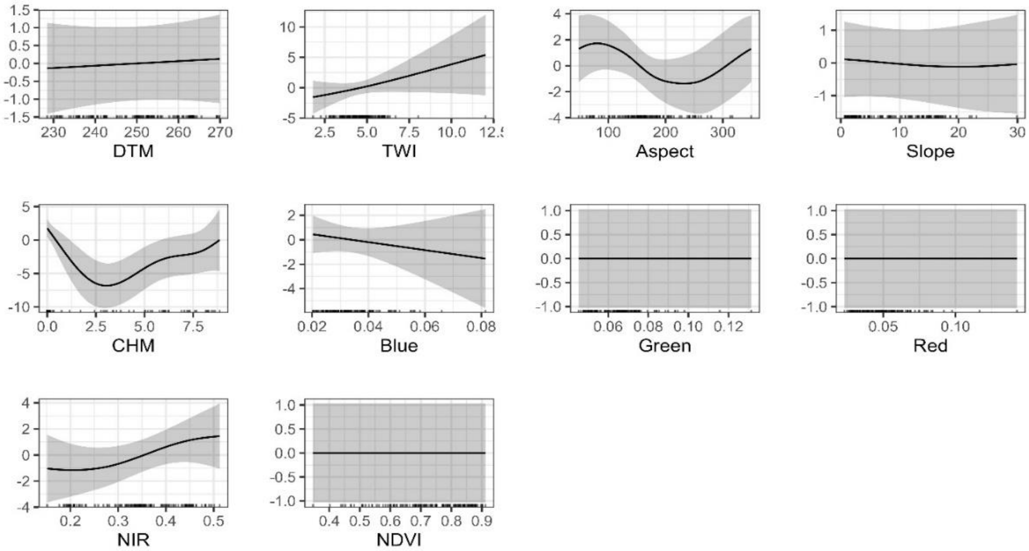

Figure 15: Partial effect plots showing the influence of explanatory variables on SWS in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

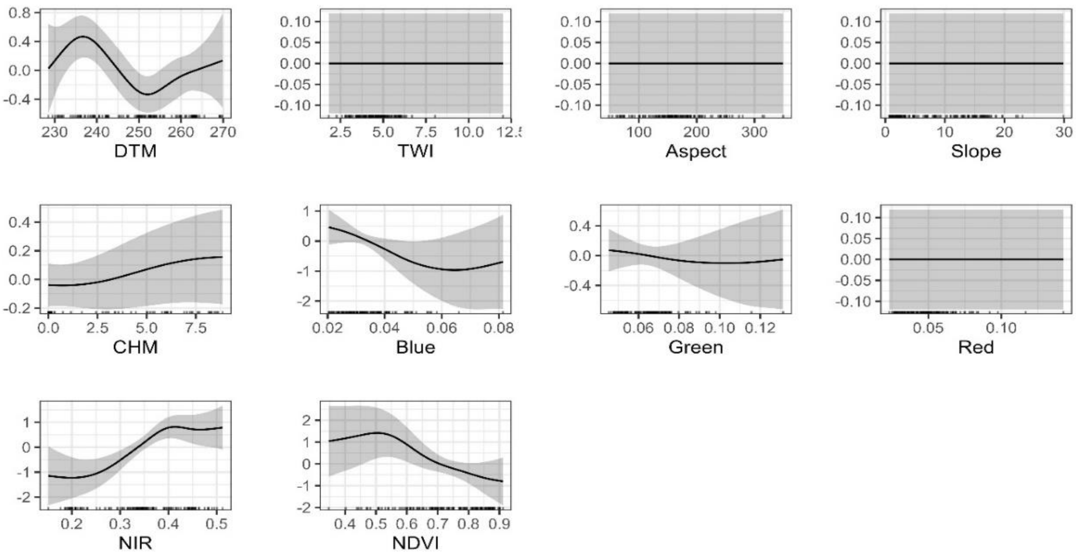

Figure 16: Partial effect plots showing the influence of explanatory variables on TN in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

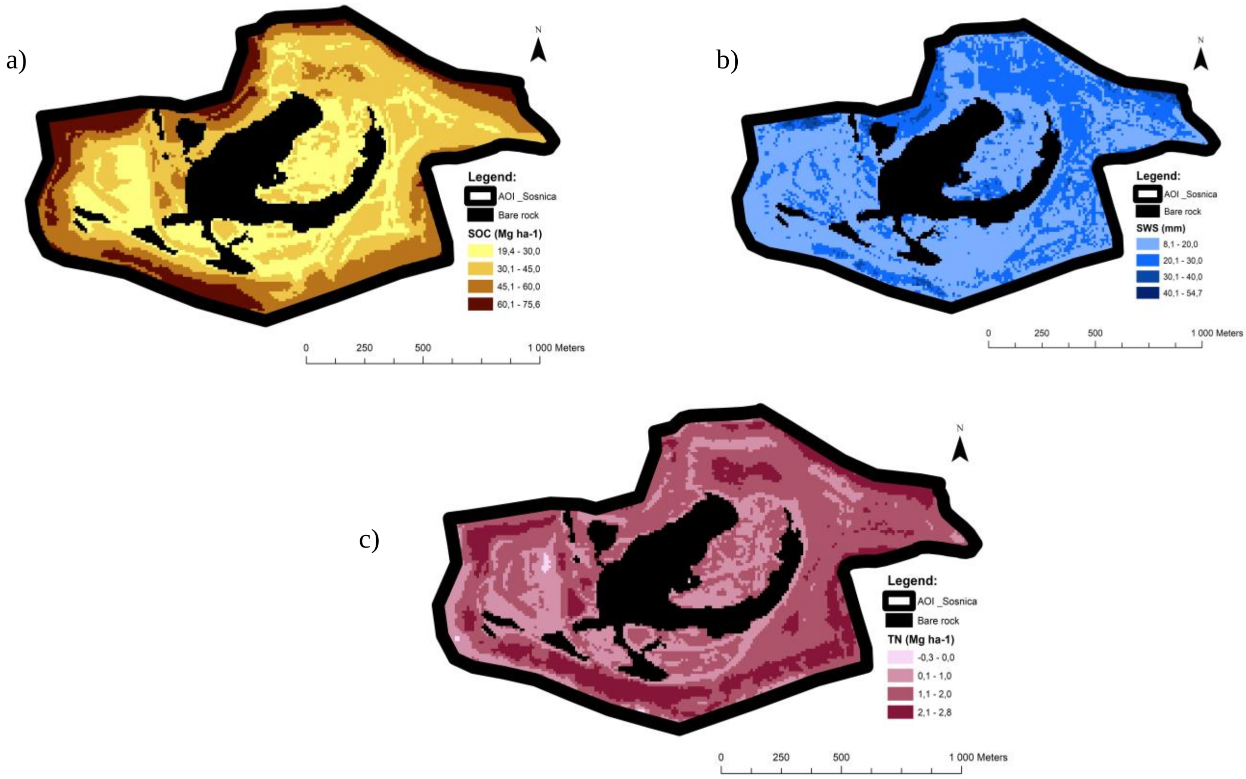

Figure 17: Spatial distribution of: a) soil organic carbon (SOC), b) soil water storage (SWS), and c) total nitrogen (TN) for the study area

The study concludes that satellite imagery and airborne laser scanning have played a key role in advancing the study of post-mining site restoration. Variables such as DTM, aspect, and blue significantly explain SOC storage, with DTM playing a critical role. TN is influenced by DTM, CHM, Blue, NIR, and NDVI, especially NIR and NDVI. TWI, aspect, CHM, blue and NIR values explain the dynamics of soil water storage, with TWI and CHM being particularly influential. In addition, targeted management of elevation, aspect, and spectral characteristics with a focus on north-facing slopes and grass cover in areas requiring water retention, such as post-mining sites, can effectively maximize SOC, SWS, and TN. These results also highlight the importance of using remote sensing technologies for a comprehensive understanding and effective management of post-mining ecosystems to promote sustainable land use practices and environmental conservation efforts.

5. Summary and conclusions

1. According to the critical review article, SOC accumulation in reclaimed mining soils (RMS) significantly increases with reclamation age, influenced by vegetation type and reclamation methods.
2. Improving soil physical parameters especially bulk density, porosity, and capillary water holding capacity is essential for effective post-mining restoration, with reclamation methods and vegetation choices critically impacting these properties; grasses and forbs enhance the topsoil, trees improve deeper layers, and grassland and forbland exhibit higher soil water storage in the uppermost layers than woodland.
3. Vegetation types and reclamation methods strongly influence SOC and TN stocks in post-coal-mine heaps, with woodland yielding the high stocks in the litter layer, topsoiling and cultivation promoting the greatest SOC and TN in topsoil layers, and grasses recommended as optimal for SOC stocks due to their consistent performance even without topsoil.
4. Reclaimed sites with topsoil showed a significant increase in C_{oLF}, emphasizing the role of enhanced humification in stabilizing SOC for continuous carbon sequestration, with grasslands playing a key role in influencing SOC fractions and contributing to carbon stabilization, thus recommending topsoiling and revegetation, particularly with grasses, to enhance SOM accumulation and increase the labile fraction in reclaimed post-mining sites.
5. The Generalized Additive Model (GAM) identified key factors influencing SOC, TN, and SWS in post-mining ecosystems, with remotely sensed variables such as DTM, aspect, and blue significantly explaining SOC storage, DTM, CHM, NIR, and NDVI influencing TN, and TWI, aspect, CHM, blue, and NIR values driving soil water storage dynamics, underscoring the importance of targeted management of elevation, aspect, and spectral characteristics, particularly for north-facing slopes and grass cover, to optimize these factors and promote sustainable post-mining ecosystem management.

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6. List of other research achievements and contributions

- **Publications not part of the PhD dissertation:**

Misebo, A.M, Mesene, M., Anjulo, A., Pietrzykowski, M. (2025). The Effects of Fanya Juu Terraces on Soil Physicochemical Properties in the Context of Sustainable Crop Production and Erosion Control in Southern Ethiopia. Land Degradation & Development. 36 https://doi.org/10.1002/ldr.5542

Woś, B., Chodak, M., Likus-Cieślik, J., **Misebo, A. M**., & Pietrzykowski, M. (2024). Regeneration of post-mining and post-fire soil function by assessment of tree nutrient status: Evidence from pioneer and N-fixing species. Land Degradation & Development, 35 (15), 4521-4534. https://doi.org/10. 1002/ldr.5237

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Pietrzykowski, M. **Misebo, A.M**., Pająk, M., Woś, B., Sroka, K., Chodak, M. (2022). Impact of Tree Species and Substrates on the Microbial and Physicochemical Properties of Reclaimed Mine Soil in the Novel Ecosystems. Forests, 13, 1858. https://doi.org/10.3390/f13111858.

Misebo, A.M., Ayano, S.F., Pietrzykowski, M. (2021). Effects of Natural Rehabilitation of Degraded Land by Exclosure on Selected Soil Physicochemical Properties in Eastern Ethiopia. Agronomy, 11, 1628. https://doi.org/10.3390/ agronomy11081628.

- **Conference & Training Participation:** Engaged in over 7 national and international conferences and training programs.
  - ✓ **2021:** Attended the **Earth and Environmental Sciences International Webinar Conference 2021** on **Zoom**, jointly hosted by the University of Zululand and Chang'an University, held on **1–2 February 2021**.
  - ✓ **2021:** Attended the **International Summer School on Restoration of Post-Mining Sites**, held on **8–12 June 2021** at Charles University, Prague, Czechia.
  - ✓ **2021:** Attended the **International Conference on Forest and Landscape Restoration of Post-Mining Sites**, held on **3–6 June 2021** in Prague, Czechia.
  - ✓ **2022:** Presented **orally** on *"Impact of Tree Species and Substrates on the Microbial and Physicochemical Properties of Reclaimed Mine Soil in the Novel Ecosystem"* at the **5th International Conference of Environmental Engineering and Design**, held on **13–14 October 2022** in Zielona Góra, Poland.
  - ✓ **2022:** Presented a **poster** on *"Impact of Different Tree Species on Soil Properties on Reclaimed Sand Pit"* at the **4th International Conference of Young Scientists: Soil in the Environment**, held on **29 May–1 June 2022** in Toruń, Poland.
  - ✓ **2023:** Delivered an **oral presentation** on *"Soil Organic Carbon and Nitrogen Storage Under Different Vegetation Types and Reclamation Treatments on*

Carboniferous Rocks in Coal Mine Heaps" at a conference organized by the **Association for Scientific and Academic Research (ASAR)**, held on **14 September 2023** in Bahir Dar, Ethiopia.

- ✓ **2023:** Attended *"How to Become a Better Teacher and Scientist"* at the **Summer University of Szczecin, Poland**.
- ✓ **2024:** Presented a **poster** on *"Soil Organic Carbon and Nitrogen Storage Under Different Vegetation Types and Reclamation Treatments on Carboniferous Rocks in Coal Mine Heaps"* at the **XXVI World Congress of the International Union of Forest Research Organizations (IUFRO)**, held on **23–29 June 2024** in Stockholm, Sweden.

- ➢ **International Internship:** Completed a two-month internship (1 April – 31 May 2024) at the Institute of Forest Ecology, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria, funded by an **Erasmus+ grant**.
- ➢ **Research Grant Award:** Secured funding under the PRELUDIUM-22 program (Grant No: 2023/49/N/ST10/01874) for the research project: *"The Impact of Tree Species Functional Groups on Carbon Sequestration and Glomalin-Related Soil Protein in Reclaimed Coal-Mining Ecosystems."*

7. List of attachments

7.1. Full text copy of the papers included in Ph.D. dissertation

7.2. Copyright statements for the papers included in dissertation

forests

Review

Soil Carbon Sequestration in Novel Ecosystems at Post-Mine Sites—A New Insight into the Determination of Key Factors in the Restoration of Terrestrial Ecosystems

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Abstract: Mining activities are one of the main causes of land degradation around the world and reduce the quality of the surrounding ecosystems. Restoration approaches using different vegetations and reclamation methods have been implemented to address this issue. In this review, paper, different studies focusing on the effect of the restoration of mining sites on the accumulation of soil organic carbon (SOC) were analyzed. SOC in reclaimed mining soil (RMS) increased considerably after various restoration efforts were implemented. The amount of SOC accumulated in RMS was mostly influenced by the restoration age, vegetation type, and substrate or type of reclamation used. From the scientific papers analyzed, we found that SOC accumulation increases with restoration age; however, vegetation type and reclamation have varied effects. According to the review, the restoration of mine sites with vegetation resulted in a rate of SOC accumulation ranging from 0.37 to 5.68 Mg SOC ha^{-1} year^{-1}. Climate conditions influenced the type of vegetation used for restoration. Regrading, liming, NPK fertilization, and seeding a mix of legumes and grasses were the most efficient reclamation techniques. Additionally, the use of grass and legume better facilitates the early accumulation of SOC compared with afforestation. Thus, the selection of appropriate tree species composition, reclamation treatments, and restoration age are the key factors for a high SOC accumulation rate.

Keywords: mining sites; novel ecosystem; soil carbon; reclamation treatments; vegetation type; restoration

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1. Introduction

In the Anthropocene, human activities, such as mining, have caused large-scale ecosystem disruptions and changes to the earth's surface [1,2]. Human activities have also altered global element cycles, including carbon, while the gradual increase in carbon dioxide content in the atmosphere continues to be a driving factor for climate change.

The removal of vegetation cover and topsoil causes a severe decrease in soil organic carbon (SOC) content, making mining one of the most significant human impacts on the environment [3,4]. Shrestha and Lal [5] found that SOC in reclaimed mine soils decreased by up to 83% when compared with undisturbed sites. Land productivity is also diminished as a result of soil profile disturbance during mining [6]. The exposed or deposited post-mining substrates become the parent rock of the developing soils called reclaimed mine soils (RMS) or Technosols [7–9]. These substrates typically display a lack of SOM, nutrient deficiency (mainly of nitrogen and phosphorus) and disturbed nutrient ratios, low pH-values, and unfavorable air–water properties [2,9,10].

When it comes to restoring the ecological function of mining sites after exploitation, two basic questions should be considered: succession or reclamation [11]? Succession does not always allow for the restoration of soil function and plant communities in a timely manner. As a result, anthropological intervention through reclamation stimulates the long-term process of succession in post-mining sites [10,12]. The reclamation of mining sites improves the productivity of the sites as well as the sequestration of lost carbon (C) and the reduction in CO_2 emissions [7]. For example, Pietrzykowski and Socha [13] revealed that Scots pine (*Pinus sylvestris* L.) productivity in post-mining ecosystems was comparable with that of a managed forest on a natural pine site. As a result, mine heap rehabilitation is critical for the restoration of ecosystem services [14,15]. The goal of reclamation (how it will be used later); natural conditions, such as climate, the availability of soil substrates, and water balance; technical (mining) management, including management of rock overburden; and the relief of the site designed for reclamation all influence the design and detailed planning of reclamation treatments [9,11,13]. In areas with a well-formed landscape, favorable hydrological conditions, and potentially productive soils, reclamation may entail using biological methods such as agricultural practices, mineral fertilization, and the introduction of appropriate humus-forming vegetation to target and skillfully accelerate soil formation processes. In places with barren or phytotoxic soils (e.g., the acidic and sulfurous Miocene sands, etc.), the basic restoration technique, in addition to appropriate landscape formation and hydrological condition regulation, consists of sealing and neutralization, followed by biological reclamation [16].

Planting vegetation is the most popular biological restoration approach for mining sites [10,17]. Mining constrains the establishment of vegetation by affecting essential soil components for plant growth, such as organic matter, microbial activity, and water, as well as by increasing bulk density and heavy metals [17–20]. Reclaiming a rehabilitation site with various methods such as topsoiling (i.e., respreading of salvaged topsoil or spreading of uppermost soil layer from surrounding arable fields), green manure such as lupine and alfalfa, biochar, inclusion of plant litters, fertilizer treatment, and planting of grass and leguminous shrubs aids in the growth of vegetation [21–23]. Planting vegetation at a mining site plays a crucial role in the production of organic matter, which supports soil biota and releases carbon and essential nutrients into the soil [15,24–28]. Improved soil organic matter may also improve the soil moisture-holding capacity and soil cation exchange, which are vital in the restoration of degraded mining soils [29]. Evaluating a mine site after restoration is vital to ensuring successful restoration. Among the reclamation quality indicators, SOC is very reliable, and evaluating its' status over time shows the quality of the reclaimed land [4,28,30–32].

The accumulation rate of SOC in a reclaimed site is affected by different driving factors, such as the age of the stand, the type of vegetation, treatments applied before restoration, the approach of rehabilitation, and agro-climate [13,28,33]. Litterfall from the planted vegetation is one of the major sources of SOC in reclaimed sites, and its accumulation over time has a direct relationship with SOC. The findings of Barliza et al. [34] in spoil heap reclaimed from an opencast coal mine in Colombia indicates that the highest fine litterfall recorded in the 21-year-old site (2.3 Mg ha^{-1} $year^{-1}$) was more than double that recorded in the 7-year-old site (1.1 Mg ha^{-1} $year^{-1}$) and concluded the enriching role of litterfall on soil organic matter content and nutrient status with the increasing age of the stand. An increase in the age of the stand also increases the microbial community [35], which results in the decomposition of organic matter and increases the amount of carbon in the soil with increasing age. Mukhopadhyay et al. [36] also concluded that age of reclamation has a significant effect on the nutritional and microbial properties of the mine soils.

Since the beginning of the history of mining, many studies have been conducted on reclamation methods for degraded mining sites to minimize its environmental impact and to enhance ecosystem services in the changing climate. Several studies have evaluated the effects of mining site reclamation on carbon sequestration [33,37–41]. It is critical to review the impact of restored novel ecosystems at post-mine sites on carbon sequestration in light of the increasing amount of greenhouse gases, including CO_2, in the Earth's atmosphere. Therefore, the objectives of this review are (i) to compile an overview of the effect of new ecosystems developed at mining sites on SOC accumulation, (ii) to summarize the key driving factors affecting the amount of carbon accumulated on reclaimed mining soil, and (iii) to provide a recommendation on reclamation approaches that enhance carbon accumulation for the restoration of mining soil.

2. Factors Affecting Carbon Accumulation in RMS

The restoration of mining sites often contributes to SOC accumulation, but its rate may be affected by different factors such as the reclamation method, the age of restoration, the climate, soil properties, soil moisture, and vegetation [17,28,33,37,42,43] (Table 1).

2.1. The Age of Restoration and Dynamics of SOC Accumulation in Restored Novel Ecosystems

A chronosequence study of reclaimed mining sites found that carbon stock increases with age [8,28,47,50,51] (Table 1), but this depends on the vegetation type. For example, the increase in SOC with age for deciduous vegetation reaches a maximum at 10 years and then increases at a slower rate, whereas for coniferous vegetation, SOC slowly increases with age up to 40 years [49]. Furthermore, Sperow [56] found that the annual rate of SOC accumulation increases at an increasing rate for the first 11 years for pasture and 13 years for forest and then decreases for the remaining 20 years. The increase in restoration age promotes the growth of various trees, shrubs, and grasses, which contribute to the addition of soil organic matter via litterfall, twigs, and roots and which also serves as a starting point for soil development in post-mining sites [57].

Carbon is added to the soil each year; therefore, the age of restoration increases the SOC. Adeli et al. [58] showed the strong and positive correlation of SOC accumulation with reclamation age for both forest and pasture ecosystems. The higher SOC at the oldest site (17 years old) was due to the accumulation of leaf litter and its decomposition, which forms humus [36]. Additionally, Adeli et al. [58] mentioned the manure addition from grazing wildlife animals as an additional source of SOC under pasture. Ahirwal and Maiti [59] revealed that afforestation with tree species showed a rate of SOC accumulation in the range of 1.2–2.8 Mg SOC ha^{-1} $year^{-1}$. As indicated in Table 1, the annual SOC ranged from approximately 0.32 Mg ha^{-1} [48,49] to 5.0 Mg ha^{-1} [33,54]; the calculated average annual increment was 1.84 Mg ha^{-1}; and the variation in the annual increment may be due to tree species, climate, and reclamation methods [33,37,42]. Similarly, Pietrzykowski and Krzaklewski [60] also reported SOC accumulation at a rate of 1.5 Mg C ha^{-1} $year^{-1}$ in mine soil in Poland. The findings of Stahl et al. [61] revealed increased SOC content with age and the 22-year-old and 32-year-old reclaimed soils had higher mean SOC contents than the undisturbed soil. This indicates that the age of restoration has a significant impact on the accumulation of SOC in RMS.

2.2. The Effect of Vegetation Types on SOC Accumulation

In the case of restoration by afforestation, the success of reclamation mainly depends on the type of plant species selected for revegetation for the particular site and climate [28]. The most common vegetations types used for restoration are mixed forest, deciduous, ever green, legumes, and grass [4,62,63]. Different tree species play different roles in amending mine soil properties even in the same climate [38,64–66]. Field experiment studies indicated significant differences in the SOC stocks under different afforested trees on the same soil substrate, which may be due to the amount of litter, the decomposition of dead roots, and the elemental composition of the individual biomass [37,67]. The decomposition of leaf litter releases the bound nutrients into the soil, which increases the SOC concentration of mine soils over time [62]. Ahirwal and Maiti [59] stated that the increase in SOC concentration is due to the accumulation of leaf litter and its subsequent decomposition to humus. Yan et al. [44] recommended Quercus liaotungensis compared with Rhus typhina and Pinus tabuliformis is associated with its significantly higher organic carbon sequestration rate (1.59 t ha^{-1} yr^{-1}) for reclamation management of degraded mining lands in China. Frouz et al. [48] also observed significantly different SOC accumulation rates among different tree species, ranging from 0.15 to 1.28 t ha^{-1} yr^{-1} in post-mining sites in the Czech Republic.

Table 1. The effect of age on soil organic carbon accumulation.

Tree Species	Age of the Plantation	SOC Total Stock (Mg ha^{-1})	SOC Accumulation Rate (Mg ha^{-1} $Year^{-1}$)	Soil Depth (cm)	MAP(mm)	MAT (°C)	Reclaimed Mine Soil Substrate Type	General Reclamation Techniques	References
Mixed Forest	5	9.11	1.82	0–20	1000	26	Coal	Top soil with mixed forest	[28]
	10	19.89	1.99						
	25	41.37	1.65						
Quercus liaotungensis	11	32.59	1.59	0–30	431.1	10.0	Coal	Leveling and top soiling	[44]
Pinus tabuliformis		16.04	0.37						
Mixed *Acacia auriculiformis*, *Sennasiamea*, *Acacia catechu* and *Dalbergia sissoo*	3	1.83	0.61	0–15	1375	25.7	Coal	Regrading of spoil materials and plantation of tree species	[8]
	7	3.65	0.52						
	10	5.82	0.58						
	15	7.60	0.51						
Prosopis juliflora	2	8.1	4.05	0–60	975	27.5	Coal	Regrading and top soiling	[33]
	3	12.6	4.20						
	4	17	4.25						
	5	19.2	3.84						
	6	27.5	4.58						
	7	32.8	4.69						
	8	45.4	5.68						
Robinia pseudoacacia L.	2	11.7	4	0–30	569	9.4	Lignite	NK fertilization, and spread of a mixture of rye and alfalfa	[45]
	14	59.8							
Dalbergia sissoo	2	1.1	0.55	0–15	1308	27	Coal	Top soiling, farm yard manure, and NPK fertilizers	[46]
	16	8.91	0.56						
Mixed Forest	5	7.02	1.40	0–25	1230	16.2	Coal	Loose-graded, hydroseeded, and NPK	[47]
	11	13.52	1.23						
	21	21.35	1.02						
Alder (*Alnus glutinosa*)	28	33.49	1.20	0–20	650	6.8	Coal	n/a *	[48,49]
Lime (*Tilia cordata*)	31	34.51	1.12						
Oak (*Quercus robur*)	28	15.01	0.54						
Spruce (*Picea* sp.)	27	8.46	0.32						
Pine (*Pinus* sp.)	22	8.80	0.40						

Table 1. *Cont.*

Tree Species	Age of the Plantation	SOC Total Stock (Mg ha^{-1})	SOC Accumulation Rate (Mg ha^{-1} Year^{-1})	Soil Depth (cm)	MAP(mm)	MAT (°C)	Reclaimed Mine Soil Substrate Type	General Reclamation Techniques	References
Casuarina equisetifolia	6	3.19	0.53	0–30	1228	21.7	Heavy mineral	Topsoil with a seed mixture of short-lived annual species	[50]
	9	3.75	0.42						
	12	9.35	0.78						
	15	11.55	0.77						
Mixed Forest	2	5.4	2.70	0–30	975	23	Coal	Only backfilled dumps	[51]
	8	16.4	2.05						
	14	26.4	1.89						
Scots pines and giant miscanthus plants.	n/a	33	n/a	0–20	n/a	n/a	Lignite	Sewage sludge	[52]
		45	n/a					Compost	
Scots pines	25	27.2	1.1	O to C2 horizon	n/a	n/a	Lignite	Liming and NPK fertilizers	[53]
		37.4	1.50					NPK fertilizers	
Scots pines	12	63.1	5.20	0–110	580	7.6	Lignite	Liming, NPK fertilization and sowing a mixture of grasses and leguminous plants	[54]
	17	45.9	2.70						
	21	22.6	1.08	0–110	700	8	Sand	Top soiling, NPK fertilization, and lupine as green manure	
	23	16.8	0.73						
	30	65.0	2.17	0–110	650	7	Sulfur	Leguminous and grass crop with NPK fertilization	
	30	34.4	1.15						
Pasture land	25	36.7	1.47	0–30	n/a	n/a	Coal	Grading and application of stored top and subsoils	[55]
Forest land		37.1	1.48						

* n/a = data is not available.

Yao et al. [68] indicated that the physical and chemical properties of the soil of a 15-year-old reclaimed coal mine improved and concluded that different tree species have varying degrees of influence on soil forming process. This may also be due to the tree species effect on the soil fauna communities, which are vital for the decomposition of litterfall. For example, the soil environment created by pine litter is relatively more unfavorable for fast decomposition [69] due to its acidic reaction that hampers development of the soil fauna community [70]. However, Zeng et al. [71] revealed that the litter decomposition rate of broad-leaved trees was significantly higher than that of coniferous evergreen trees, which may result in the difference in carbon input into the soil. Similarly, Šourková et al. [72] suggested that vegetation type has a greater impact on the microbial community than the substrate and measured the highest values of microbial biomass under oak and alder compared with pine trees. Trees with good litter quality exhibit higher microbial biomass carbon. Moreover, the existence of microorganisms in soil can increase soil aggregation and can enhance soil fertility by improving the nutrients [73,74]. These increase the C storage potential of the soil by creating conducive environments that facilitate the establishment of mosses, lichens, and herbaceous and perennial plants [75].

Vegetation affects soil respiration by influencing the soil microclimate and structure, the quantity of detritus supplied to the soil, the quality of that detritus, and the overall rate of root respiration [76]. Tewary et al. [77] found that the soil respiration rates beneath coniferous trees were lower than those beneath broad-leaved trees in a mixed forest in northern India. Pietrzykowski [78] also mentioned the value of the selective choice of tree species for afforestation of post-mining areas to accelerate the development of technogenic soil substrates. Therefore, the selection of the right tree species is a prime concern for SOC improvement in RMS due to the unfavorable mine spoil characteristics, such as high rock fragments (60–80%), low water-holding capacity, low pH, high bulk density, poor microbial activity, and low nutrient content [51,79].

The difference in vegetation cover also resulted in significant variations in the rates of carbon accumulation at the same age in different ways. For example, Sperow [56] estimated that pasture had higher soil C sequestration rates than forest soil. Rehabilitation using grass enhanced the early accumulation of SOC in RMS compared with the others, which may be due to grass land accumulating larger portions of carbon in soil while forests allocate large portions in biomass. Chatterjee et al. [80] also observed a maximum accumulation of SOC in grass land at 9 years (29.5 Mg ha^{-1}) after reclamation and an almost similar amount after 30 years (29.7 Mg ha^{-1}). The findings of Shrestha and Lal [20] indicated that 81% of carbon is accumulated in tree biomass such as aboveground biomass, roots, and litter and that the remaining 19% of the carbon is accumulated in the soil in a forest ecosystem. Similarly, 77 to 82% of carbon accumulation in plant biomass in the forest ecosystem was also reported by Amichev et al. [81]. In the grass land ecosystem, however, 84% of carbon was accumulated in the soil [20]. Akala and Lal [37] observed that 48 Mg ha^{-1} of SOC was stored in forest after 21 years and that pasture stored 55 Mg ha^{-1} of SOC after 25 years.

However, not all studies confirm the higher C sequestration under pastures compared with forests at post-mining sites. As indicated in Table 1, a study conducted in the USA in conditions of reclaimed post-mining soils showed that the SOC sequestered at a 0–30 cm depth in post-mining soils over 25 years was similar for pastures and forest [55]. A study conducted in reclaimed mine soils in Ohio (USA) showed that the conversion of pastures to Australian pine (*Casuarina* spp.) and Black locust (*Robinia pseudoaccacia* L.) increased the SOC pool in the top 50 cm of soil [39]. Some studies revealed a higher amount of SOC accumulation under legume vegetation types than grass elsewhere. For example, the study of Kumari and Maiti [62] revealed that the rates of SOC accumulation (1.57 Mg SOC ha^{-1} year^{-1}) under legume were higher than that for grass. Legumes showed advantages over the grass species in restoring mine soil fertility.

Climate determines the type of vegetation used for afforestation, and therefore for the accumulation of SOC in RMS. For a better accumulation of SOC, Vindušková and Frouz [49] suggested that grasses should be planted at warmer sites, that conifers should be planted at colder sites, and that deciduous trees should be planted at intermediate sites. Soil moisture is also an important factor in the accumulation of organic carbon in the soil. A higher SOC accumulation is observed where the moisture content is high. For example, the findings of Li et al. [63] indicated that moisture level had an effect on carbon accumulation. A higher moisture content results in high biomass production, thereby increasing the accumulation of organic carbon in forest soil.

Additionally, inputs of organic matter from plantations of different tree species positively influence the C, N, and P contents, pH, water-holding capacity (WHC), and bulk density (BD) of the RMS [36,58]. Izquierdo et al. [82] revealed a decrease in BD after planting trees in the degraded mining sites. The soil loosens due to soil organic carbon following the growth and development of roots decreases soil bulk density [37]. Additionally, different research indicated significant increases in the C, N, and P contents and WHC due to the accumulation of litterfall and decomposition, forming humus [20,83,84]. All of these improvements enhance the growth of diversified plants, and soil development thus increases carbon storage in RMS.

2.3. The Effect of Reclamation Treatments on SOC Accumulation

The reclamation of degraded mine soil facilitates easy establishment of vegetations by improving the physical and chemical properties of the soil substrate, thereby improving the SOC. The most commonly applied mining site reclamation methods are backfilling, regrading, and applying topsoil [8,28,51]; forming and leveling of the surface, hydroseeding [47], and adding topsoil with a seed mixture of short-lived annual species [50]; and adding green manure, using mineral fertilization with NPK, and liming [21,60]. All of the listed reclamation methods significantly improved the severely degraded mining site substrate to support plant growth. Reclamation of the mine site with the addition of topsoil and spreading a mixture of grass seeds before afforestation of fast-growing trees accounted for 9.03 Mg C ha^{-1} stock in a 5-year-old reclaimed coal mine dump, which is five-fold higher than that of an unreclaimed mine [59]. Similarly, the results of Čížková et al. [85] indicated the high potential of reclaimed grasslands with topsoil for C sequestration, measured up to 1.6 Mg ha^{-1} y^{-1}. Thus, the application of topsoil creates more suitable conditions for soil organic matter accumulation.

The substrate varies significantly due to the variation in applied reclamation and therefore variation in SOC. Pietrzykowski et al. [21] recommended one year of lupine green manure cropping for the restoration of mine soil prior to vegetation due to its contribution of 13.55 Mg ha^{-1} of SOC compared with two-year lupine cultivation (9.5 Mg ha^{-1}), one-year fallow and two-year lupin cultivation (10.23 Mg ha^{-1}), and two-year fallow and lupin cultivation (8.4 Mg ha^{-1}). However, the parent material also strongly determines the SOC accumulation even under the same reclamation methods applied. In another comparative study of soil development under succession and after reclamation in the same area, Pietrzykowski and Krzaklewski [60] found significantly higher SOC accumulation in reclaimed soils.

Antonelli et al. [86] also indicated that the amendment of biosolids in mine site reclamation after 13 years has the significant influence on SOC sequestration (6.3 Mg ha^{-1} yr^{-1}) compared with in an unamended mine site (0.72 Mg ha^{-1} yr^{-1}). Thus, the application of any of the reclamation methods enhances colonization of microorganisms and early establishment of vegetation that contributes to SOC accumulation in RMS. However, a gap still exists between studies comparing the effects of mine site soil reclamation methods on SOC accumulation.

3. Conclusions

The restoration of mine soil is a global issue that needs scientific investigation due to the vulnerability and complexity of mining sites. The factors associated with mining, such as top soil removal, compaction, contamination, and removal of organic matter result in drastic changes in the physicochemical properties of mine soil. Restored mining sites perform ecological functions important for increasing the resilience to climate change in the environment and provide important ecosystem services, among which C sequestration is regarded as the most significant. Experimental studies have shown that the restoration of mining sites increase soil organic carbon sequestration. However, the amount of SOC accumulation in RMS is mainly affected by the development rate of restoration, the vegetation type, the climate, the soil moisture, and the substrate or type of reclamation applied. The implementation of reclamation greatly facilitates successful occupation of microorganisms and establishment of plants at the site. These findings also reveal that inoculating microorganisms such as bacteria, cyanobacteria, or a combination of them increases the sequestrated C in the soil. The effect of restoration on SOC is predominantly found to be specific to species, reclamation methods, and age. Thus, choice and management of appropriate reclamation methods and tree species require a detailed understanding of the substrate type and climatic factors for successful accumulation of SOC in RMS. Even though reclamation enhances the successful establishment of planted trees, the number of cost–effect studies is lacking. Therefore, the cost effectiveness of different reclamation methods and its effect on SOC storage studies are recommended.

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RESEARCH ARTICLE

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The interactive effect of reclamation scenario and vegetation types on physical parameters of soils developed on carboniferous mine spoil heap

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Abstract

Bulk density, porosity, and water retention capacity play a key role in limiting root growth and nutrient uptake in developed technogenic soils. Thus, the purpose of this study was to evaluate the impact of reclamation technologies and different vegetation types on vital physical soil properties formed from carboniferous materials. The case study was conducted on Sosnica hard coal post-mine spoil heaps (Upper Silesian Coal Basin of Southern Poland). Nine experimental combinations of reclamation technologies and vegetation types were tested. For vegetation types and basic physical soil parameters, 120 plots (10 × 10 m) were selected. The texture analysis was done on composite soil samples collected at two uppermost soil depths (0–10 and 10–20 cm). Intact structure samples were collected into 100cm^3 cylinders from the middle of each plot at both depths for bulk density (BD), porosity, capillary water capacity (CWC), and soil water storage (SWS). In the comparison of different reclamation scenarios, we noted that topsoiling increased BD, whereas porosity decreased. Spontaneous succession had the same effect on BD, porosity, and CWC as cultivation. Revegetation of the spoil heap with grasses and forbs resulted in lower BD and higher porosity and CWC in the top layer (0–10 cm), whereas woodland resulted in lower BD and higher porosity and CWC at lower depths (10–20 cm). The decreasing order of the SWS was grassland > forbland > woodland. Thus, forbs and grasses should be followed by tree planting, which is crucial to improving the hostile physical properties of the Carboniferous postmine soils.

KEYWORDS
bulk density, capillary water capacity, hard coal, porosity, post mine

1 | INTRODUCTION

The mining of coal and lignite, oil shale, mineral sand and rock, sulfur, and metallic mineral deposits has geomorphological, hydrological, and chemical effects on all ecosystem components (Feng et al., 2019; Shan et al., 2005; Wei et al., 2001). Globally, coal and lignite continue to play an important role in the energy mix, and postmine landscapes resulting from exploitation activity are examples of large-scale transformation and human disturbance of ecosystems and are of worldwide interest and concern (Prasad et al., 2018; Zhang et al., 2019).

From an ecological point of view, the goal of the reclamation of post-mine sites is to develop a long-term sustainable possess all ecosystem functions and structures (Ahirwal & Maiti, 2022; Pietrzykowski, 2008). However, the produced mining residues and rock wastes could have unfavorable properties for ecosystem development, such as nutrient deficiency, extremely high heavy metal concentrations, a lack of recent organic matter from plant litterfall, compaction, and poor soil-water relationships (Brevik & Lazari, 2014; Macdonald et al., 2015; Mukhopadhyay & Maiti, 2011). Furthermore, off-site pollution from mining activities was observed in the form of acid mine drainage caused by the oxidation of sulfide minerals (Kim & Chon, 2001). In addition, the disturbances of mine soil physicochemical properties also changed dynamically during development and due to mining site reconstruction and spatial patterns. Thus, reclamation and reconstruction of mine soil function are the key issues for restoration (Zhen et al., 2019).

Reclamation of mined sites improves soil properties, such as organic matter, microbial activity, soil moisture-holding capacity, and soil cation exchange, which are critical in the restoration of degraded mining soils (Frouz et al., 2009; Restrepo et al., 2013). Among soil properties, bulk density (BD), water-holding capacity, and porosity are the most important parameters that can affect vegetation survival and growth in reclaimed mining soil by restricting root growth and nutrient uptake (Keller et al., 2013). They also determine the plant-water relationship, water retention, and nutrient leaching (Indoria et al., 2020).

BD is predominantly used to estimate soil carbon storage and calculate soil physical quality (Vereecken et al., 2016); whereas water retention capacity and soil porosity are related to soil BD, soil organic matter (SOM), and soil texture (Stephens et al., 2003). BD and porosity are also the major physical factors influencing soil water storage (SWS), which is an important indicator of available water and for developing management strategies in water-stressed ecosystems (Kuráž, 2001). Reclaimed mining heaps are a typical water-stressed ecosystem, with plant growth and ecosystem functions limited by the soil water. However, excessive compaction harms the physical, chemical, and biological properties of the post-mining soil (Rabot et al., 2018).

Mining activities and reconstruction, including topsoiling, use heavy machinery, resulting in high BD due to compaction (Pan et al., 2017). When reclaiming, salvaging, and handling wet topsoil may also result in compaction (Shrestha et al., 2005), Twum and Nii-Annang (2015) observed an adverse influence of mining site compaction on BD and root biomass after 85 years of reclamation, which resulted in high BD, the horizontal growth of roots, and high root biomass in the upper layer (Lipiec et al., 2003). This indicates that it has a long-term impact and is not only harmful to young trees but also to old trees, which are more vulnerable to lack of nutrition and uprooting as a result of high winds (Nicoll et al., 2006). Relationships between soil compaction, spatial variability in BD in reclaimed mining sites due to soil-rock mixing and reclamation technology, as well as vegetation types are critical for the novel ecosystem's development.

Several researchers discovered that reclamation and long-term vegetation restoration reduced BD significantly (Cao et al., 2015; Lin et al., 2020; Zhang et al., 2015; Zhao et al., 2013). Other studies, however, have found that spontaneous succession reduces BD in the post-mining heap in the same way that costly and labor-intensive reclamation and topsoiling do (Cejpek et al., 2013; Kołodziej et al., 2017; Zhu et al., 2016). This disparity also calls for more research into the effects of reclamation technology and vegetation types on post-mining soil BD.

Although BD plays an important role in reclaimed novel ecosystems by impeding revegetation and the effectiveness of reclamation technology, there have been very few studies on spatial variability (Huang et al., 2021; Wang, Cao, et al., 2020) and the effect of reclamation (Cao et al., 2015; Kołodziej et al., 2017; Lin et al., 2020; Zhao et al., 2013). But it lacks compressive analyses of how reclamation techniques and vegetation types affect BD. As a result, it is necessary to investigate how functional characteristics of vegetation and various reclamation technologies affect BD, porosity, and water retention capacity of developed technosols. We hypothesized that differences in BD, porosity, and water retention capacity in soils formed in post-mining novel ecosystems are primarily caused by reclamation technology and functional groups of vegetation. Therefore, the goal of our research was to assess the impact of reclamation technologies and vegetation types (woodland, forbland, and grassland) on the BD, porosity, and water retention capacity of soils formed from carboniferous rock.

2 | MATERIALS AND METHODS

2.1 | Study site

The study site was the "Sośnica" hard coal post-mine spoil heap in Gliwice and Zabrze (50° 16′ 22″ N, 18° 44′ 43″ E), Upper Silesian Coal Basin, Southern Poland. The regional climate is classified as temperate, with an average annual precipitation of 727 mm and an average annual temperature of 8.5°C. Hard coal has been mined for over 250 years and covers approximately 170 hectares with a height of more than 30 m (Kompała-Bąba et al., 2021). The spoil heap is composed of carboniferous rocks, primarily shale, sandstone, and their conglomerate (Prasad et al., 2018). It has unfavorable soil texture, poor water retention, a fast-drying surface layer, low SOM content, and nutrient availability, and often high salinity and geogenic carbon content (Cabała et al., 2004; Kompała-Bąba et al., 2019).

The reclamation of the mining heap began with the grading of mine spoils from overburden removal. Following grading, large portions of the areas were reclaimed with topsoil. Planting of various vegetation (trees, forbs, and grasses) was only carried out on the areas reclaimed with topsoil. Twenty-five years ago, also, the spontaneous succession of different vegetations began on both reclaimed and unreclaimed mine spoil heaps (Kompała-Bąba et al., 2019). The most common vegetations in woodland are *Robinia pseudoacacia*, *Betula pendula*, *Populus tremula*, *Pinus sylvestris*, *Populus hybrid*, *Larix decidua*, *Populas nigra*, *Padus serotine*, *Alnus glutinosa*, *Salix alba*, and *Quercus robur*; in grassland are *Calamagrostis epigejos*, *Festuca ruba*, *Arrhenatherum elatius*, and *Poa compressa*; and in forbland are *Lupinus polyphyllus*, *Melilotus alba*, *Tussilago farfara*, *Chamaenerion palustre*, *Solidago gigantea*, *and Daucus carota*.

2.2 | Soil sampling and analyses

2.2.1 | Soil sampling

A reconnaissance survey was carried out to gain a thorough understanding of the novel ecosystem's reclamation technology and vegetation types. The fragments of the investigated spoil heap where the research plots were located were then classified into nine variants of the experiment based on reclamation technologies and vegetation types using land monitoring, documentation, and remote sensing data (Figure 1). Totally, 120 research plots with 10 × 10 m were randomly established on the identified experimental patches of the spoil heap (Figure 2).

Out of 120 research plots, 60 were established on spontaneous succession (forbland, grassland, and woodlands from succession under barren rock and topsoiling) with 10 replications on each variant, whereas 60 were established on active reclamation (topsoil cultivation) with 10 replicates of each variant on forbland (*L. polyphyllus* and *Melilotus alba*), grassland (*Festuca ruba* and *Arrhenatherum elatius*), and woodlands (*Robinia pseudoacacia* and a mixture of different species, such as *Betula pendula*, *Alnus glutinosa*, and *Larix decidua*) based on dominance and area coverage. Boreholes were dug on each plot with soil drills, and mixed samples (weighing approximately 1.0 kg when fresh) were collected (from 4 points at the corners and one in the middle of each plot). For particle size determination, 240 composite soil samples were collected from depths of 0–10 cm and 10–20 cm for each plot. To determine BD, porosity, capillary water capacity (CWC), and SWS samples of the intact structure were collected into 100cm^3 cylinders from the middle of each plot at both depths, a total of 240 samples.

2.2.2 | Laboratory analyses

In the laboratory, the collected soil samples were dried to a constant weight at 65°C and passed through a 2 mm mesh sieve to remove any debris, rocks, and large plant debris (such as leaves, twigs, and roots) before particle size determination analysis. The Fritsch GmbH Laser Particle Sizer ANALYSETTE 22 was used to measure soil texture spectrally. For the determination of BD, porosity, CWC, and SWS, the undisturbed soil samples were weighed (initial soil water content), saturated by capillarity for 48 h, and weighed again. Soil samples were then dried at 105°C for 48 h and weighed again. BD (g/cm^3) was calculated by dividing the mass of oven-dried (105°C) by the volume of its cylinder (Sumner, 2010).

$$\mathrm{BD}\left(\mathrm{g/cm^3}\right) = \frac{\mathrm{Ms}}{\mathrm{V}} \tag{1}$$

where BD, soil BD (g/cm^3); Ms, mass of soil after oven drying (g); V, bulk volume of the soil (cm^3).

CWC% was computed as the difference between soil water content at saturated and after oven-dried (105°C) by dividing its volume.

$$\mathrm{CWC\%} = \frac{\mathrm{W1} - \mathrm{W2}}{\mathrm{V}} \times 100 \tag{2}$$

where CWC%, capillary water capacity in percent; W1, weight of soil after saturated by capillarity for 48 h (g); W2, weight of soil after oven drying (g); V, bulk volume of the soil (cm^3).

Porosity (P) was calculated by the relationship between BD and particle density using the following equation (Sumner, 2010):

$$\mathrm{P\%} = 1 - \mathrm{BDPD} \times 100 \tag{3}$$

where P%, Porosity in percent; BD, soil bulk density (g cm^{-3}); PD, particle density (g cm^{-3}).

The SWS to a depth of 0–10 cm and 10–20 cm was calculated using the following equation (Zhang & Shangguan, 2016):

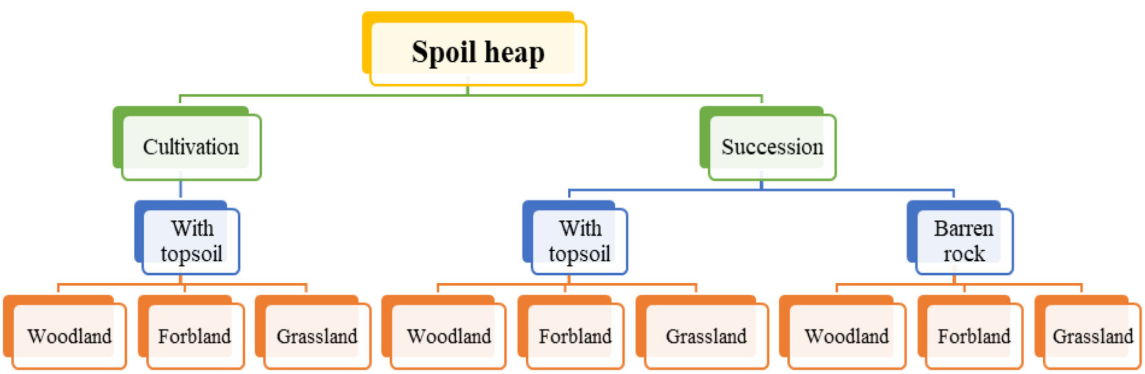

FIGURE 1 Figure presenting nine experimental variants indicating reclamation scenarios and types of vegetation. [Colour figure can be viewed at wileyonlinelibrary.com]

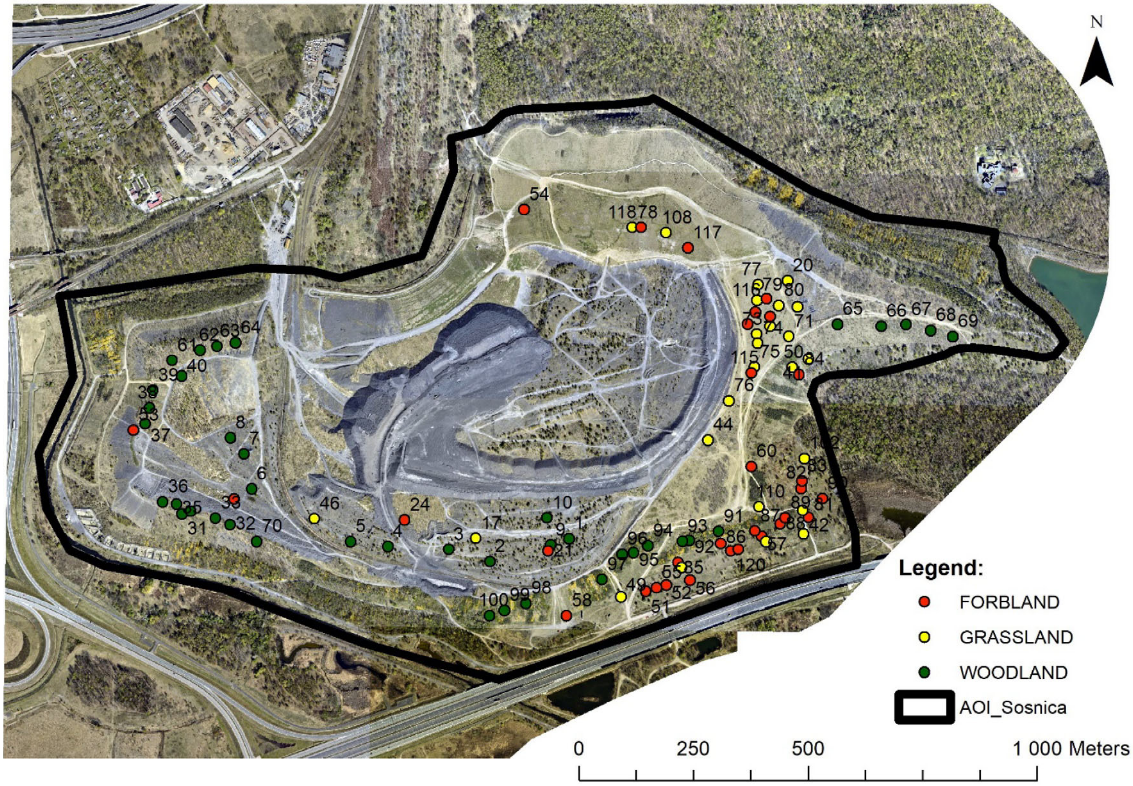

FIGURE 2 Map of the study site. [Colour figure can be viewed at wileyonlinelibrary.com]

$$SWS = \theta v \times h \times 10 \quad (4)$$

where SWS is the soil water storage at a specific depth (mm), θv is the volumetric SWC at a specific depth ($cm^3\ cm^{-3}$), and h is the soil depth increment (cm).

2.3 | Statistical analysis

To evaluate the effect of reclamation technologies and vegetation types on the studied physical properties (BD, porosity, CWC, and SWS), statistical analyses were conducted using Statistica 12.0 Software (StatSoft, Inc. 2014). Mean, standard deviations, analysis of variance (ANOVA), and Tukey's HSD (honestly significant difference) were calculated. Prior to analysis, the normality of distributions was tested using the Shapiro–Wilk test. All means were considered different when $p < 0.05$. Distribution maps of BD and SWS were prepared using the Ordinary Kriging interpolation method (ArcGIS software, Esri).

3 | RESULTS

3.1 | Soil texture

Soil texture differed significantly under reclamation treatment but not under vegetation types. Exceptionally substrate at 0–10 cm depth under forbland contains less clay than substrate under woodland and grassland. Sites reclaimed with topsoil had significantly higher silt content (ranging from 43% to 48%) than areas without topsoil (ranged 31%–34%). Sands and clays were significantly higher in areas without topsoil than in areas reclaimed with topsoil (Table 1).

3.2 | The effect of reclamation and vegetation types on bulk density, porosity, and water retention

Reclamation techniques and vegetation types had a significant effect on BD and porosity at both depths, but there was no significant interaction effect between vegetation and reclamation. CWC is significantly affected by vegetation types and interactions only at 0–10 cm depth (Table 2, See Figure 3).

The significant effect of reclamation (topsoil application and without topsoil) was observed only in BD at 0–10 cm and BD and porosity at 10–20 cm under woodland. However, there was no significant difference in porosity and CWC at 0–10 cm, CWC at 10–20 cm for all vegetation types, and BD under grassland and forbland at both depths. Topsoil application significantly increased BD under woodland in both depths but decreased porosity at 10–20 cm (Figures 4 and 5).

The methods for introducing a vegetation type to a mining heap (succession and cultivation) only affected BD and porosity at 10–20 cm under woodland. However, there is no difference in BD, P, and

TABLE 1 Soil texture in studied technosols under different reclamation treatment and vegetation types at 0–10 and 10–20 cm depths.

		Reclamation treatment		Vegetation types		
Texture (%)	Depth (cm)	Without topsoil	With topsoil	Woodland	Grassland	Forbland
Sand	0–10	59 ± 14^{a}	49 ± 14^{b}	51 ± 13^{a}	48 ± 15^{a}	55 ± 15^{a}
	10–20	54 ± 13^{a}	42 ± 16^{b}	44 ± 14^{a}	46 ± 15^{a}	45 ± 19^{a}
Silt	0–10	31 ± 10^{b}	43 ± 13^{a}	40 ± 12^{a}	43 ± 14^{a}	38 ± 14^{a}
	10–20	34 ± 10^{b}	48 ± 14^{a}	45 ± 12^{a}	43 ± 14^{a}	45 ± 16^{a}
Clay	0–10	10 ± 4^{a}	8 ± 2^{b}	9 ± 2^{a}	9 ± 3^{a}	7 ± 2^{b}
	10–20	12 ± 4^{a}	10 ± 3^{b}	11 ± 3^{a}	11 ± 4^{a}	10 ± 4^{a}

TABLE 2 Two-way ANOVA results for reclamation and vegetation types impact on bulk density (BD), porosity, and capillary water capacity (CWC).

		Reclamation		Vegetation types		Reclamation × vegetation types	
Parameters	Depth(cm)	F	*p*	F	*p*	F	*p*
BD	0–10	21.63	0.00	3.83	0.02	ns	ns
	10–20	23.78	0.00	3.05	0.04	ns	ns
Porosity	0–10	19.28	0.00	3.60	0.03	ns	ns
	10–20	22.26	0.00	4.22	0.02	ns	ns
CWC	0–10	ns	ns	14.67	0.00	4.56	0.01
	10–20	ns	ns	ns	ns	ns	ns

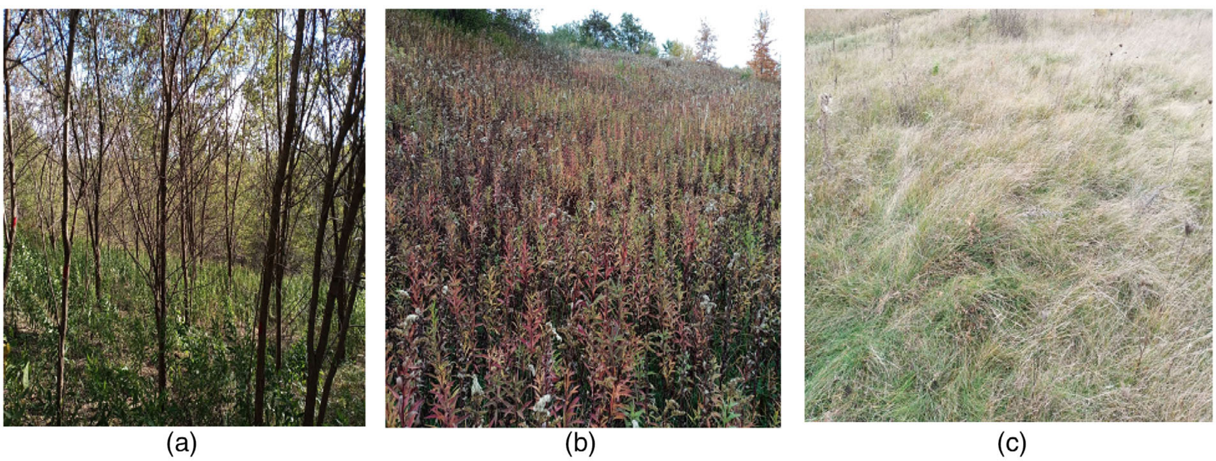

FIGURE 3 Selected vegetation types developed on the mining heap; (a), woodland with *Robinia pseudoacacia*; (b), forbland with *Solidago gigantea*; (c), grassland with *Festuca rubra* (photo by A.M. Misebo). [Colour figure can be viewed at wileyonlinelibrary.com]

CWC at 0–10 cm, and in CWC at 10–20 cm for all vegetation types. Only at 10–20 cm depth, succession was reduced by BD and increased porosity significantly under woodland (Figures 6 and 7).

The effect of vegetation types on BD, porosity, and CWC of the uppermost soil layer varies with depth. In 0–10 cm depth, forbland had a lower BD content than woodland, but woodland had a significantly lower BD content than both grassland and forbland in 10–20 cm depth. However, porosity was higher in forbland than in woodland in the 0–10 cm depth and significantly higher in woodland than in both grassland and forbland in the 10–20 cm depth. CWC was higher in grassland and forbland than in woodlands at 0–10 cm depth, but there was no difference at 10–20 cm depth (Figure 8). In general, the difference between depths resulted in an increase in BD with depth for all vegetation types. The opposite was observed for porosity and CWC, which showed a decrease in the second layer of soil for the same types of vegetation (Figure 8).

3.3 | Soil water storage

SWS differed significantly in both layers between the vegetation types. The grassland and forbland had higher SWS than woodland. The mean value of SWS under grassland and forbland tended to increase with soil depth, whereas it decreased under woodland

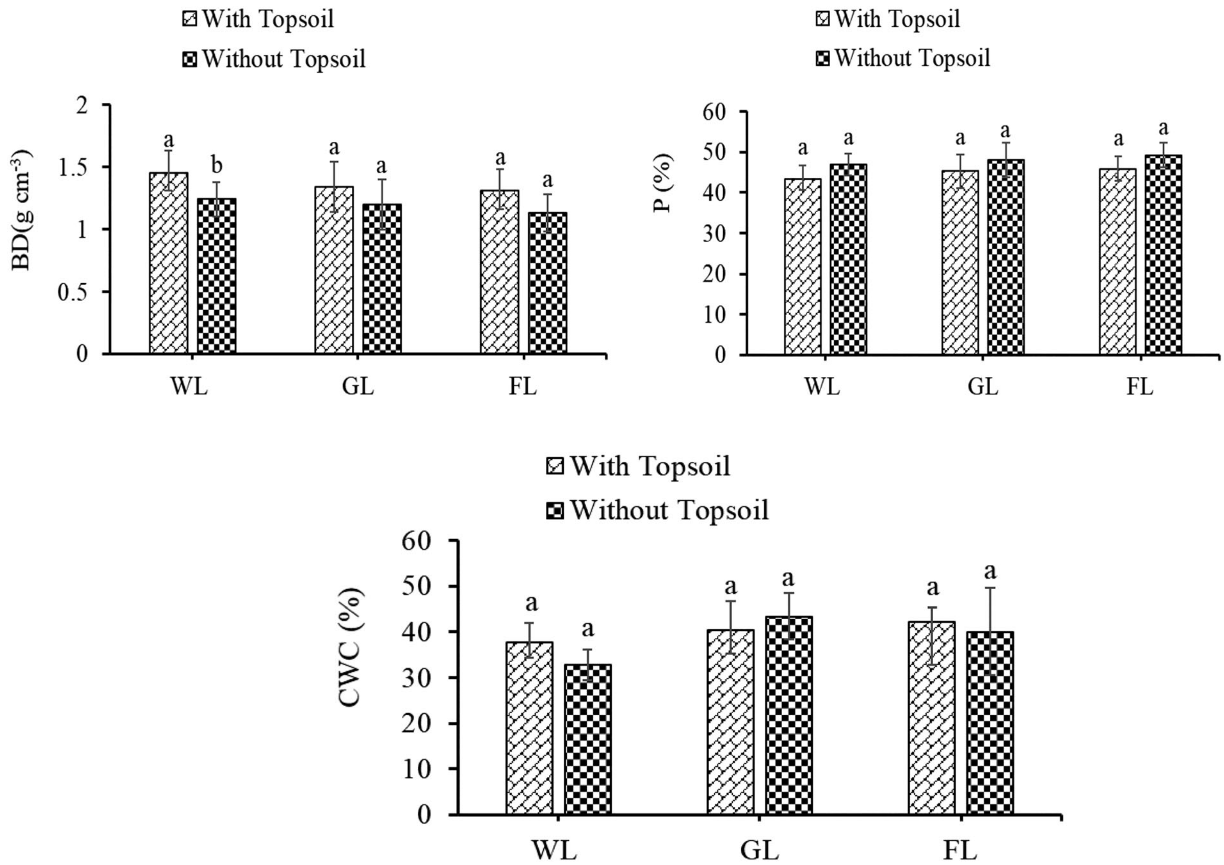

FIGURE 4 The effect of reclamation (with topsoiling and without topsoiling) on BD, porosity (P), and WCW under vegetation types at 0–10 cm; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a, b) are significantly different (at $p < 0.05$).

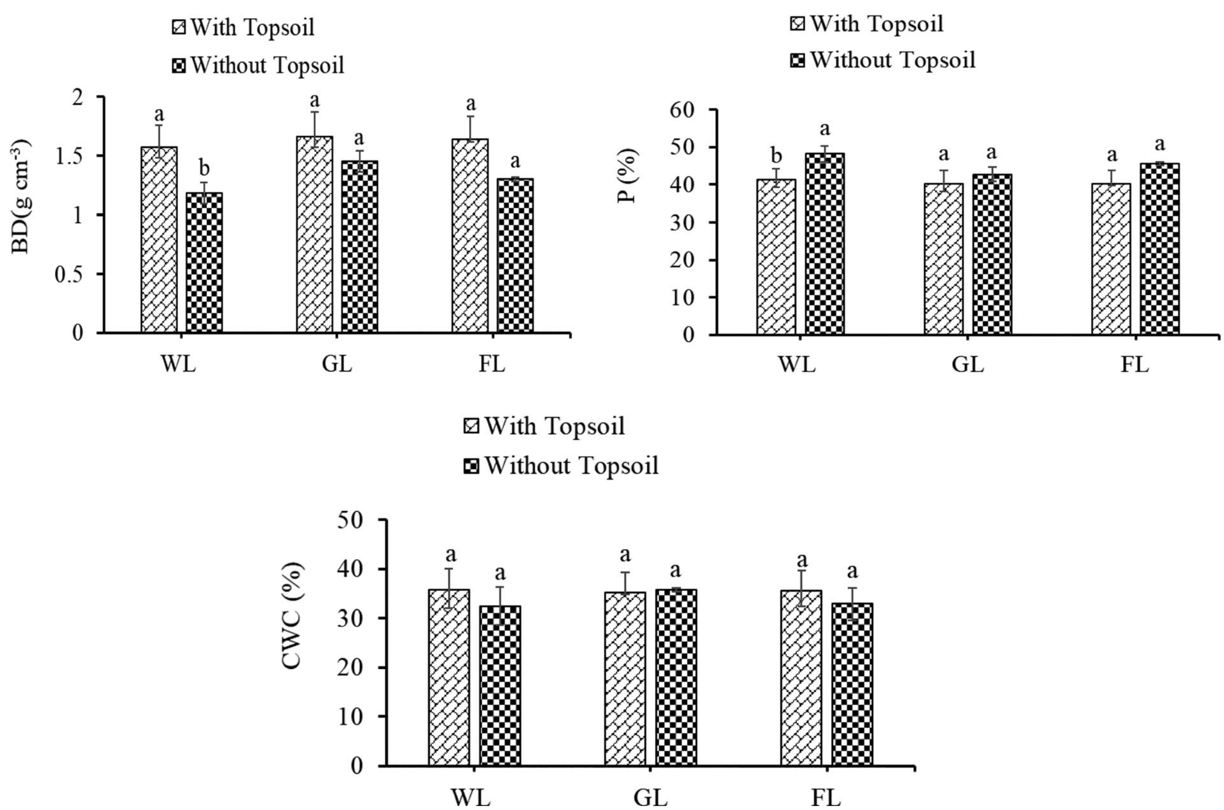

FIGURE 5 The effect of reclamation (with the application of topsoil and without topsoil) on BD, porosity (P), and WCW under vegetation types at 10–20 cm; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a, b) are significantly different (at $p < 0.05$).

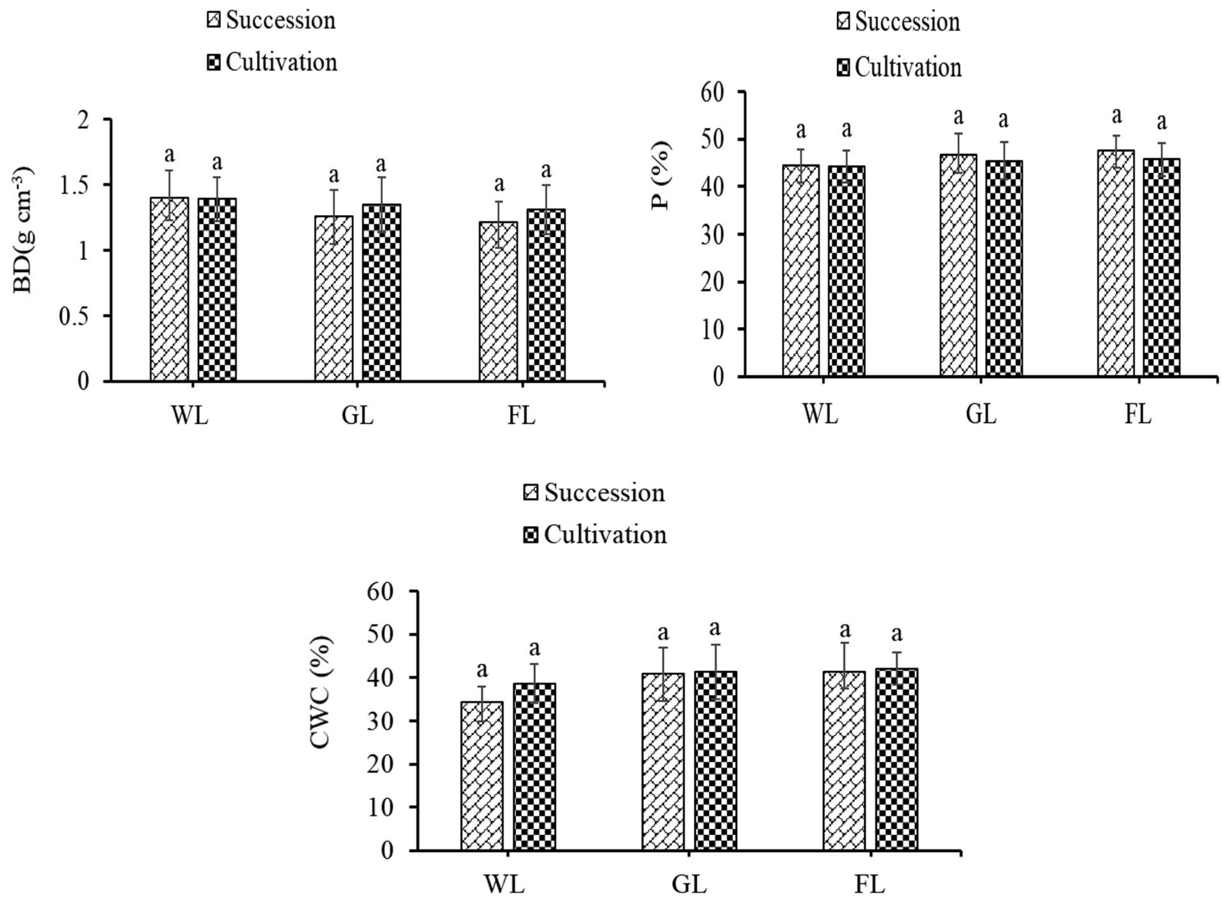

FIGURE 6 The effect of succession and cultivation of vegetation types on BD, porosity (P), and WCW at 0–10 cm; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a,b) are significantly different (at $p < 0.05$).

(Figure 9). The mean CV of SWS was higher in the woodland, indicating that SWS was variable in the woodland (Table 3).

3.4 | Spatial distribution of BD and SWS

The spatial distribution of the BD and SWS in both soil layers was striped and patchy. At depths of 0–10 cm, the BD gradually increased from southwest to northeast, whereas at depths of 10–20 cm, the BD gradually increased from east to west (Figure 10). Based on the vegetation types distribution (Figure 2), the BD at 0–10 cm under grassland and forbland was lower than tunder woodland, but at 10–20 cm the lowest was observed under woodland. The distribution of SWS showed higher values in the east and lower values in the west for both depths, following the distribution pattern of the vegetation types (Figure 11). According to Figure 2, the higher spatial distribution values in both depths were observed under grassland and forbland.

4 | DISCUSSION

There were no significant differences in the sand, silt, and clay under the three different vegetation types, except for a slight difference in clay under forbland at 0–10 cm soil depth (Table 1). As a result, comparisons of woodland, grassland, and forbland soils can be attributed to differences in vegetation types because vegetation is a key factor in the soil formation process (Jenny, 1994). The restoration of mining sites with various vegetation types promotes the improvement of selected soil water retention properties, such as BD, porosity, and capillary water holding capacity. However, the effect of vegetation types varied with depth; the influence of grassland and forbland was highest at the top layer (0–10 cm), whereas the influence of woodland was highest at the second layer (10–20 cm).

Soil BD was lower in forbland and grassland than in woodland at top depth (0–10 cm), with grassland and forbland reducing BD by 6% and 9%, respectively, when compared to woodland. However, woodland had significantly lower ($p < 0.05$) BD at 10–20 cm soil depth, reducing BD by 12% and 8%, respectively, when compared to grassland and forbland. The lower BD found under grassland and forbland compared to woodland at the 0–10 cm soil depth is probably due to forbland and grassland having high root biomass, which increases organic matter addition through litter and root decomposition at the top layer (Antony et al., 2022; Jobbágy & Jackson, 2000). The majority of forbs in our study area are legumes, such as *L. polyphyllus* and *Melilotus species*, which produce a lot of root biomass in the top layer of soil (Fornara & Tilman, 2008), which is vital for improving soil

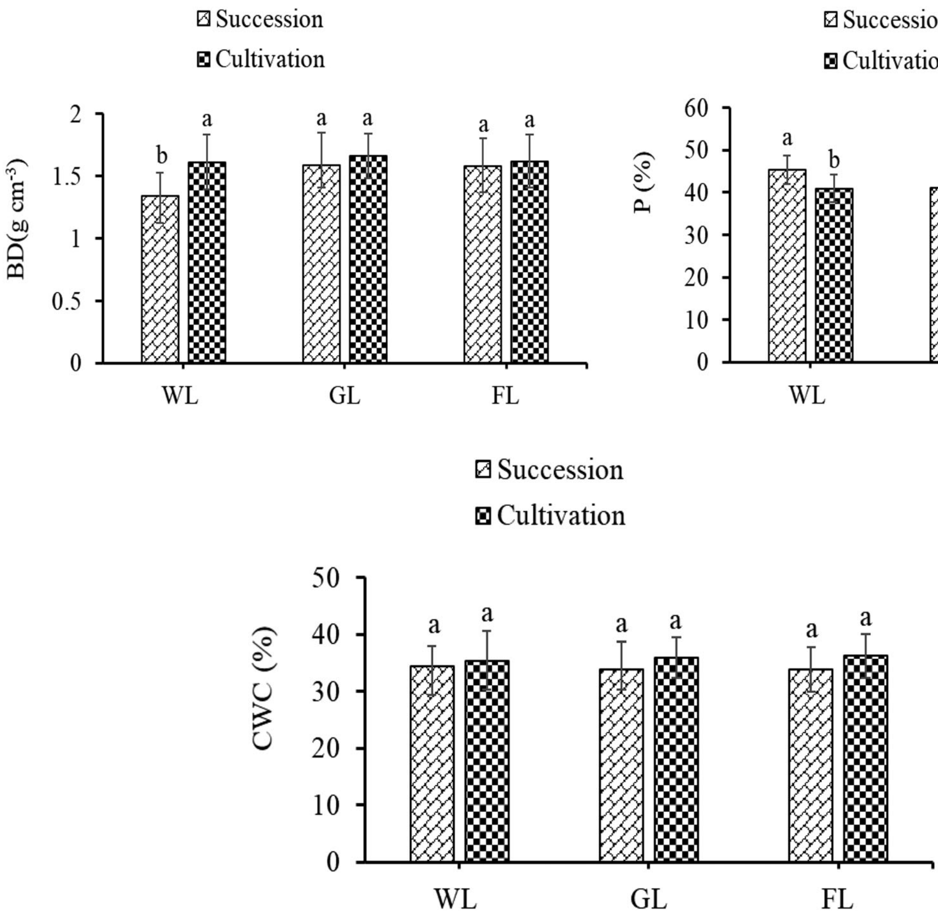

FIGURE 7 The effect of succession and cultivation of vegetation types on BD, porosity (P), and CWC at 10–20 cm; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a,b) are significantly different (at $p < 0.05$).

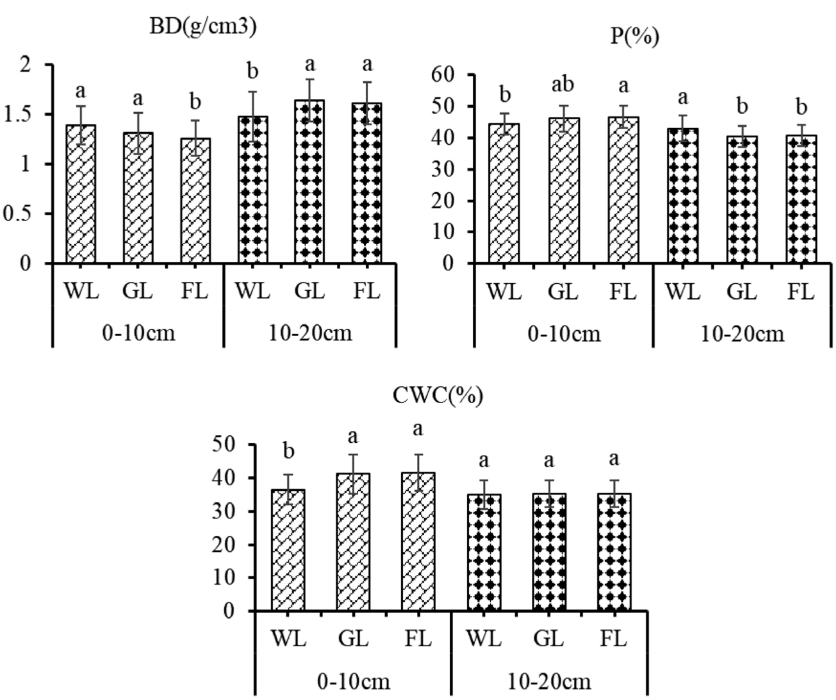

FIGURE 8 The effect of vegetation types on BD, porosity (P), and CWC of the reclaimed novel ecosystem soil at 0–10 cm (at left) and 10–20 cm (at right) depths; WL- woodland, GL-grassland, and FL-forbland; means followed by different lowercase (a, b) are significantly different (at $p < 0.05$).

properties. Grasses and forbs add organic matter to the soil in the form of dead roots, which decompose to form humus and bind the soil particles to form more soil aggregates (Dietz et al., 2020; Li et al., 2016). Similarly, Neary (2011) revealed a higher content of SOM in the surface soil horizon under herbaceous plants than in forests and woodland. However, the deeper root penetration into the parent material and significantly higher root biomass (Archer et al., 2001; Hibbard et al., 2001) and soil microbial biomass (McCulley et al., 2004) in woodland compared to grass and forbland may be the cause of the lower BD under woodlands at the lower soil layer (10–20 cm). The BD of reclaimed mining sites decreases as more roots penetrate the soil and porosity increases with reclamation progress (Wali, 1999), organic matter accumulation, and the microbial community (Feng et al., 2019).

The lower BD under grassland and forbland at topsoil depth resulted in significantly higher porosity and CWC of the soil when compared to woodland at the same depth. Similarly to BD, the volume of very fine roots is the most important root trait that affects SWS capacity, and grassland and forbland have a high volume of fine roots

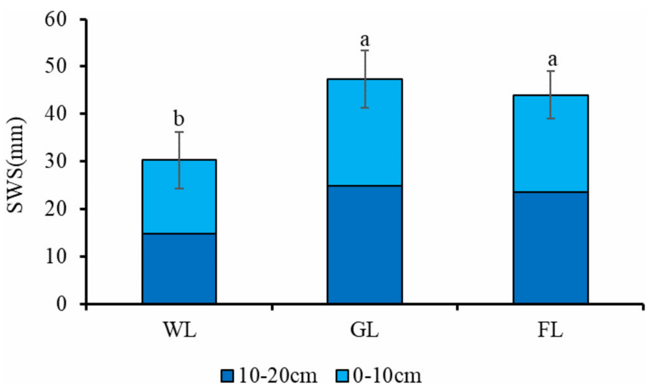

FIGURE 9 SWS under vegetation types along depths; WL-woodland, GL-grassland, and FL-forbland. The different letters between different vegetation types indicate significant differences at $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

at the top layer (Song et al., 2022). However, the deep root growth and decay of the woodland have resulted in significantly high porosity at the lower depth than grassland and forbland.

Reclamation of post-mining sites with topsoil influences substrate properties, such as increasing organic matter (Borůvka et al., 2012; Frouz et al., 2009), increasing nutrient availability (Prach & Hobbs, 2008), influencing the microbial community and activity (Six et al., 2006; Wang, Li, et al., 2020), and thus improving soil physical properties. In contrast, higher BD is observed in this study with topsoil reclamation than unreclaimed, with no difference in porosity or CWC. This could be due to heavy machinery traffic during topsoil transport and grading (Akala & Lal, 2001; Ganjegunte et al., 2009). Cejpek et al. (2013) found that topsoil spreading during reclamation does not result in improved soil moisture conditions 20 years later in their comparative study of reclaimed and unreclaimed lignite mine sites. Shrestha and Lal (2008) also mentioned higher BD (1.55 to 1.86 $Mg m^{-3}$) as a result of heavy machinery used during the mining and reclamation processes. In line with this, Čížková et al. (2018) found higher BD in the upper soil layer of reclaimed sites than in unreclaimed sites. Thus, the most effective way to solve the high BD problem is to loosen compaction during topsoil application and immediately establish vegetation (Feng et al., 2019).

The impact of revegetation methods, such as cultivation and natural succession, does not differ significantly, except for high BD and low porosity under cultivated woodland at lower soil depths, which is primarily due to the application of topsoil during woodland cultivation. The technical reclamation of mining sites results in a rapid maturation process of mine soils, which are used for the growth of grasses and trees; however, the highest heterogeneity and complexity of mine soils remain a persistent challenge for rapid productivity and ecosystem sustainability (Feng et al., 2019). Besides the effectiveness of technical reclamation in reducing the risk of uncontrolled erosion, toxin leaks, and nutrient deficiency, spontaneous succession is equally effective in improving the BD, porosity, and CWC of mining sites. This is primarily due to the colonization of plants with extensive root systems during spontaneous succession, which positively influences the

TABLE 3 Statistical summary of soil-water storage (SWS) under vegetation types in soil layers along the 0–20 cm profile.

		SWS (mm)			
Vegetation types	**Soil depth (cm)**	**Min**	**Max**	**Mean**	**CV**
Woodland	0–10	3.66	28.90	15.49	40.25
	10–20	5.81	29.00	14.77	46.38
	0–20	10.04	55.58	30.26	37.94
Grassland	0–10	10.24	33.88	22.55	28.51
	10–20	10.37	32.68	24.77	23.67
	0–20	20.61	64.90	48.39	22.81
Forbland	0–10	5.58	32.81	20.44	32.27
	10–20	10.26	31.84	23.58	24.80
	0–20	15.84	59.26	44.09	24.59

Abbreviation: CV, coefficient of variation.

soil's physical state (Kołodziej et al., 2017). Zhu et al. (2016) also found increased porosity (43.88%–58.24%) due to spontaneous plant colonization over the last 20 years, indicating the potential of natural succession in improving the hostile physical environment of mineral processing residue disposal sites.

SWS is the ability of soil to supply water and could be an important indicator for novel ecosystem function and an additional landscape and mining disturbance mitigation. It is primarily determined by soil physical properties, such as BD and porosity, SOM, and vegetation types. Comparisons of the three vegetation types developed on technosols in the restored ecosystem in both soil depths showed that grassland had the highest SWS, followed by forbland, while woodland had the lowest value (Figure 9). In woodland, the lowest and most variable SWS may result from the highest soil BD and vegetation transpiration (Seneviratne et al., 2010). Furthermore, woodlands in the study area have tree species with bigger diameters and heights than grassland and forbland, which could indicate intensive water utilization and loss from the soil because higher aboveground biomass is related to soil water consumption via root uptake (Craine et al., 2002; Jia & Shao, 2013). Lower SWS in the bottom layer of woodland may be associated with higher root concentrations in the bottom layer and a greater reliance on bottom layer water (Frouz et al., 2008; Moreno et al., 2005). This is also consistent with Cubera and Moreno (2007), who revealed that increasing depth decreases water storage under trees while increasing it under herbaceous plants.

The highest SWS under grassland and forbland was also attributed to root distributions, which caused differences in water storage and changes in vital soil physical properties, such as BD and porosity. Thomas and Jansen (1985) revealed that grass vegetation develops soil structure faster than trees in coal mine spoils. Grasses had low

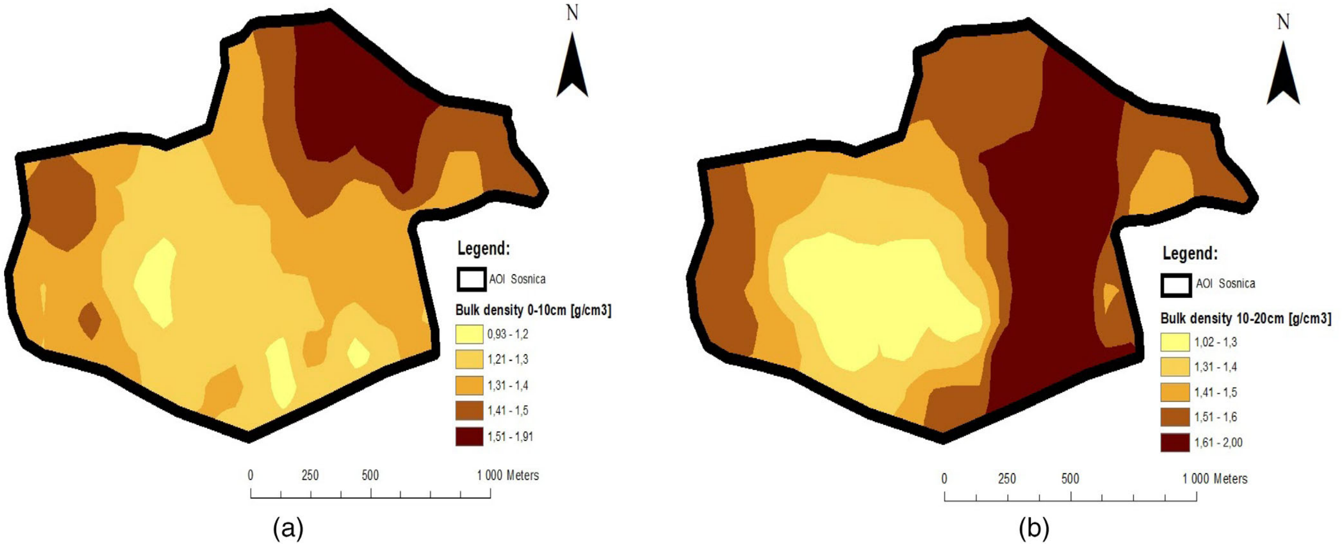

FIGURE 10 Spatial distribution maps of BD at 0–10 cm (a) and 10–20 cm (b) soil depths. [Colour figure can be viewed at wileyonlinelibrary.com]

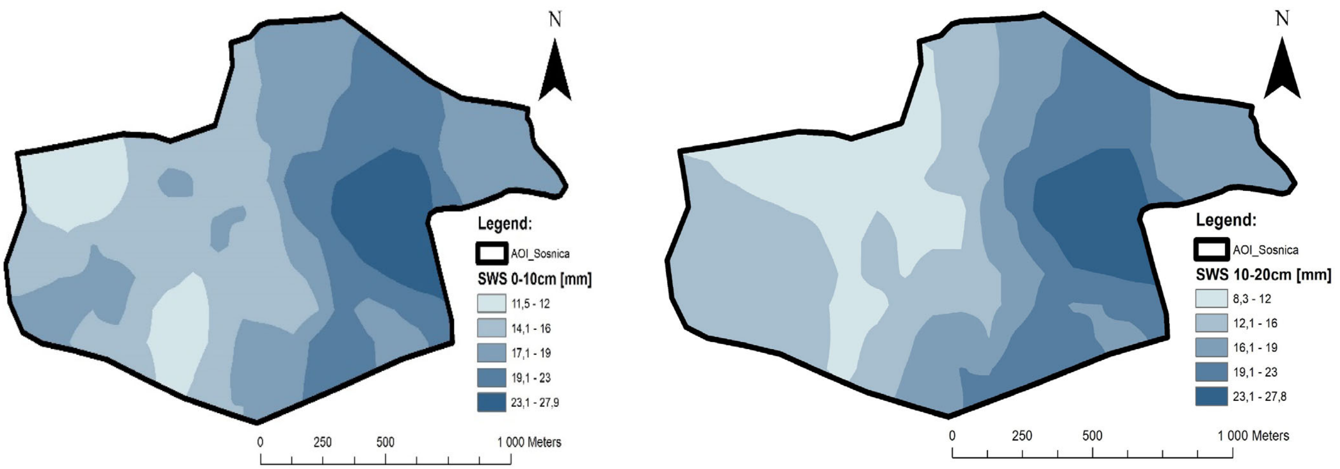

FIGURE 11 Spatial distribution maps of SWS at 0–10 cm and 10–20 cm soil depths. [Colour figure can be viewed at wileyonlinelibrary.com]

water consumption in the deeper layers due to the distribution of relatively shallow roots (Zhang & Shangguan, 2016). They have extensive fibrous root systems, which are different root features of trees in woodland (Maiti, 2013), resulting in increased soil porosity and water storage on the uppermost top layer.

5 | CONCLUSIONS

The key factor for spoil heap restoration is soil physical parameters improving, where the reclamation technique and types of vegetation are crucial in enhancing the vital physical soil properties for the functioning of the restored ecosystem services. However, the improving role of vegetation varied with soil depth. Revegetation with grasses and forbs with an intensive root system and biomass could help in reducing BD and increasing porosity and CWC at the top layer (0–10 cm), whereas growing trees had a significant influence at the second layer (10–20 cm), which is mainly related to the role of a root system. The application of topsoil resulted in the highest BD compared to unreclaimed, indicating heavy machinery traffic during topsoil transport and grading. Spontaneous succession had a similar effect on BD, porosity, and CWC as cultivation. The improved BD and porosity resulted in a higher SWS under grassland, followed by forbland, while woodland had the lowest value. As a result, to improve the hostile physical environment of the post-mining heap holistically, grass and forb revegetation should be followed by tree planting. Finally, reducing heavy vehicle traffic frequency and loosening compaction during topsoil application are effective ways to reduce soil compaction.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no known competing financial interests nor personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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RESEARCH ARTICLE

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Soil organic carbon and nitrogen in a carboniferous spoil heap as a function of vegetation type and reclamation treatment

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Abstract

Evaluating the impact of vegetation types and reclamation methods on soil organic carbon and nitrogen in carboniferous spoil heaps is critical for selecting the best vegetation type and reclamation method to improve ecosystem services in a changing climate. This paper presents the relationship between vegetation types (woodland, forbland, and grassland) and reclamation techniques (barren rock, topsoil application, succession, and cultivation) on soil organic carbon (SOC) and total nitrogen (TN) in developing soils on carboniferous rocks in coal mine heaps. Soil samples were collected from the litter layer (Oi + Oe) and the A horizons (0–10 cm). The results revealed that vegetation types and reclamation methods significantly affected SOC and TN stocks. Woodland exhibited higher SOC and TN in the Oi + Oe horizons than other vegetation types. Topsoil application and cultivation resulted in the highest SOC and TN stocks in the A horizons (0–10 cm) under woodland and forbland compared to succession on bare carboniferous rock. In grassland, there was no significant difference in SOC stock under topsoil application and cultivation; however, significantly higher TN stock was observed in the 0–10 cm areas with topsoil application compared to succession on bare carboniferous rock. Based on the results, topsoil application is recommended to improve SOC if the mining site is restored using woodland. Conversely, grassland exhibits a similar amount of SOC stock with or without topsoil application. Considering the difficulty of obtaining topsoil, we suggest that grasses are optimal for SOC stock in the studied mining sites, followed by forbs.

KEYWORDS
coal mine, reclamation, soil organic carbon, succession, topsoil

1 | INTRODUCTION

Globally, natural landscapes are changing because of the many natural and anthropogenic factors (Johnson et al., 2017; Seidl et al., 2017). Among the anthropogenic factors, large-scale mining activities significantly disturb ecosystems (Frouz & Vindušková, 2018; Martins et al., 2020; Pietrzykowski & Daniels, 2014). Mining results in massive overburden dumps containing rock fragments, underutilized fallow land, pollution, and CO_2 emissions (Ahirwal & Maiti, 2017; Pietrzykowski et al., 2021). The spoil heaps formed as a result of coal mining overburden are devoid of recent soil organic matter (SOM) and nutrients. They also have poor physicochemical and biological properties, limiting the quality and functions of the soils formed from spoil heaps (Ussiri & Lal, 2005).

At post-mining sites, the soil is formed either from overburden (spoils) as a parent material, often facilitated by succession (Macdonald et al., 2015; Uzarowicz et al., 2020; Woś et al., 2022), or by the application of topsoil (Vindušková & Frouz, 2013). Overburden materials generally have low or no recent soil organic carbon (SOC) (Fettweis et al., 2005) from litterfall. Furthermore, reclaimed topsoil has lower SOC than undisturbed soils due to mineralization losses during storage and manipulation (Akala & Lal, 2001; Shrestha &

Lal, 2011). SOC and total nitrogen (TN) are soil properties that serve as indicators of reclaimed mine soil quality and the rate of pedogenesis (Bandyopadhyay et al., 2020; Pietrzykowski, 2014). SOC is essential for improving soil properties; it can enhance the soil structure and increase its porosity, aeration, and water-holding capacity (Six & Paustian, 2014; Yan et al., 2020). The increased carbon input from litter and belowground biomass due to the revegetation of spoil aids SOC accumulation. The identification of vegetation types and reclamation techniques with high storage capacities is vital to enhance SOC accumulation and potentially mitigate global climate change (Chung et al., 2012; Yan et al., 2020).

The vegetation types used for restoration play a significant role in carbon cycling by storing carbon in biomass, SOM, and litter. Different vegetation types and reclamation technologies at mining sites affect SOC and TN storage with different organic matter input rates, decomposition rates, and organic matter distribution at various soil depths (Frouz, 2008; Singh et al., 2022; Zhang et al., 2013). A quantitative review by Vindušková and Frouz (2013) revealed significantly lower soil carbon storage in coniferous forests than in grasslands and deciduous forests on reclaimed post-mining sites in the Northern Hemisphere. Zhang et al. (2020) also demonstrated a higher accumulation of SOC and TN under grassland than under woodland in reclaimed mine soils on the Loess Plateau of China. Sroka et al. (2018) highlighted the significant role that black alder (*Alnus glutinosa*) played in the accumulation of SOC and TN in sandy mine soils. Woś et al. (2022) also observed the effect of tree species distribution on carbon stock (C_{stock}) in the organic and mineral horizons, finding that pine resulted in higher C_{stock} in the Oi + Oe horizons. In contrast, alder generated higher C_{stock} values in the 0–5 cm soil horizons compared to non-nitrogen-fixing tree species. In terms of reclamation, significantly higher SOC accumulation was observed at sites reclaimed with topsoils than with bare rock (Akala & Lal, 2001; Bartuška et al., 2015; Čížková et al., 2018). In addition, Pietrzykowski and Krzaklewski (2007) measured SOC and TN accumulation rates that were three times higher and five times higher, respectively, in reclaimed soils than in successional soils.

Different studies have been conducted on the effect of reclamation on SOC at different post-mining sites (e.g., Akala & Lal, 2001; Bartuška et al., 2015; Frouz & Vindušková, 2018; Pietrzykowski & Daniels, 2014; Pietrzykowski & Krzaklewski, 2007; Placek-Lapaj et al., 2019; Singh et al., 2022; Woś et al., 2022; Yan et al., 2020; Zhang et al., 2020). They have mainly focused on reclamation technology, individual biotic elements, and abiotic ecosystems. However, little is known about the comprehensive effects of vegetation types and reclamation technologies on SOC and TN. Therefore, this study's novelty lies in its comprehensive analysis of the impact of different vegetation types and reclamation technologies on SOC and TN. We hypothesize that the SOC and TN stock could be improved compared to natural succession by reclamation treatment and vegetation cover types on post-mining spoil heaps after coal mining. Therefore, the study's specific objectives are to determine the impact of vegetation types (woodland, forbland, and grassland) and reclamation technologies (active reclamation with topsoil, and passive with succession) on the SOC and TN stocks of coal mine heaps.

2 | MATERIALS AND METHODS

2.1 | Study site

The study was conducted in southern Poland at the Sośnica hard coal post-mining spoil heap (50° 16′ 22″ N, 18° 44′ 43″ E) in Gliwice and Zabrze, Upper Silesian Coal Basin. The site has an average annual temperature of 8.5°C and a mean annual precipitation of 727 mm. Hard coal was mined at the site for more than 250 years (Kompała-Bąba et al., 2021). The spoil heap deposits comprise carboniferous rocks, primarily shale, sandstone, and conglomerates. They have poor water retention, low SOM content and nutrient availability, and high geogenic carbon (fossil) content (Cabała et al., 2004). Reclamation activities include forming and leveling the surface, applying topsoil, and cultivating various tree species, forbs, and grasses were implemented. Partly, a succession of different vegetation types occurs on reclaimed topsoil and unreclaimed bare rock (Kompała-Bąba et al., 2019). The age of all sites ranged from 20 to 25 years. The most common vegetation in the study area was *Arrhenatherum elatius*, *Chamaenerion palustre*, *Calamagrostis epigejos*, *Festuca rubra*, *Solidago gigantea*, *Daucus carota*, *Melilotus alba*, *Populus tremula*, *Pinus sylvestris*, *Betula pendula*, *Alnus glutinosa*, *Salix alba*, *Robinia pseudoacacia*, *Padus serotina*, *Populus* hybrids, *Populus nigra*, and *Lupinus polyphyllus*, which is an alien plant.

2.2 | Soil sampling and laboratory analyses

The soil sample for this study was collected from both active reclamation plots, where the introduction of vegetation (including grasses, shrubs, and trees) occurred through reclamation (topsoiling); and passive reclamation plots, characterized by the natural succession of grasses, shrubs, and trees, with and without applied topsoil. Totally, 130 research plots with 10 × 10 m were randomly established on the identified experimental patches of the spoil heap. Out of 130 research plots, 60 were established on spontaneous succession (forbland, grassland, and woodlands from succession under bare rock and topsoil application) with 10 replications in each variant, whereas 60 were established on active reclamation (topsoil application and cultivation) based on dominant species and large area coverage; on forbland 10 replications each on *L. polyphyllus* and *Melilotus alba*, on grassland 10 replications each on *Festuca ruba* and *Arrhenatherum elatius* and on woodlands 10 replications on *Robinia pseudoacacia* and 10 replications on a mixture of different species, such as *Betula pendula*, *Alnus glutinosa*, and *Larix decidua*. On the barren rock, 10 replications were established (Figure 1).

Limited soil development on bare overburden and unweathered rock fragments results in significant geogenic carbon presence in the parent material. To address this, only soil samples from the uppermost top layer were collected to minimize its impact. Samples from the litter layer (Oi + Oe) and uppermost mineral horizons (0–10 cm depth, A horizon) were collected from each plot in October 2021. A composite soil sample for each plot was collected from five subsamples (4 points at the corners and one in the middle of each plot). For the bulk density (BD) calculation, two independent samples of 0–10 cm

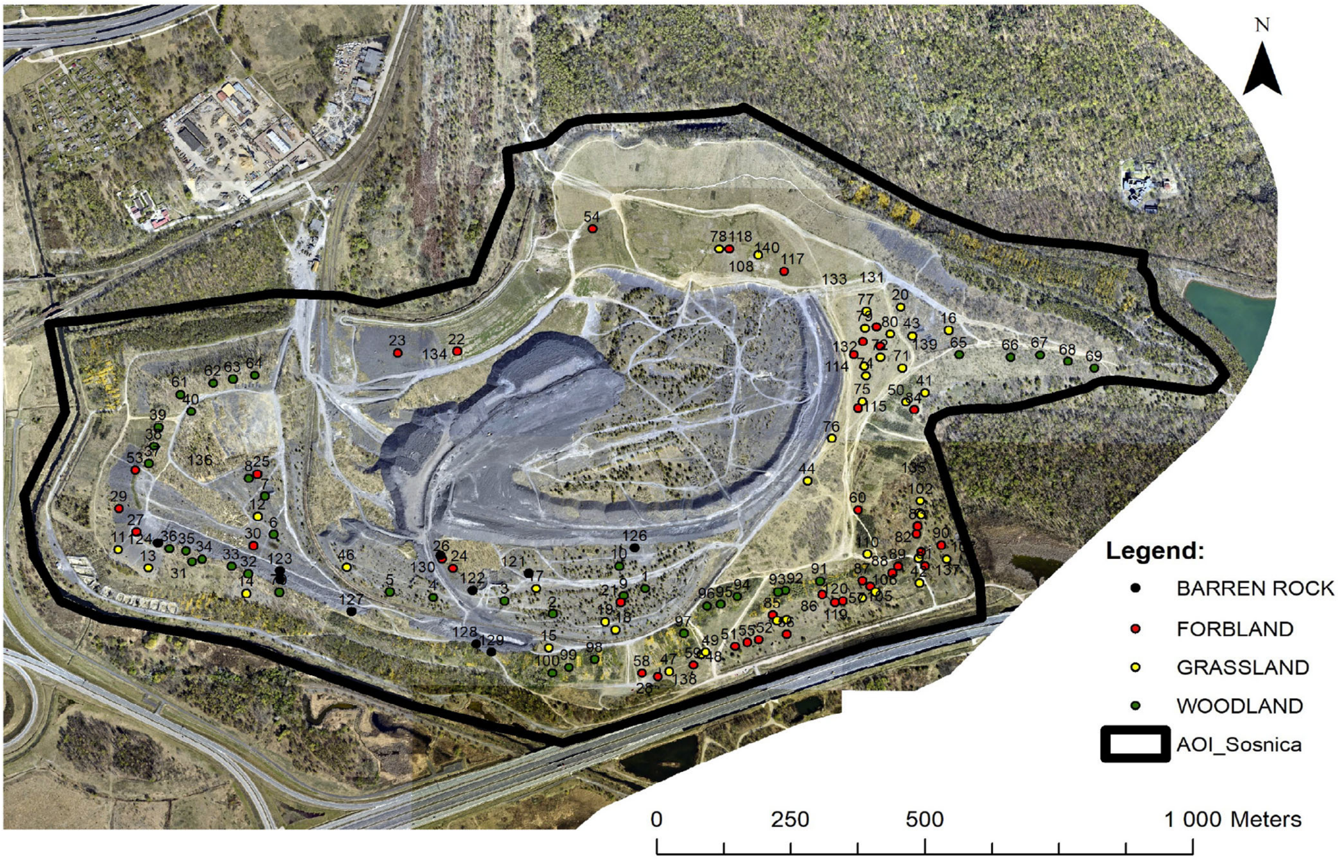

FIGURE 1 Map of the study site. [Colour figure can be viewed at wileyonlinelibrary.com]

depth per plot were taken from the center with intact structures via collection in 100-cm^3 cylinders. The litter layer (Oi + Oe) samples were collected from five 20 × 20 cm squares in each plot.

The fresh weight of the organic horizons was measured with an electronic scale and oven-dried to remove moisture before the weight of the dry mass was calculated. The composite sample of organic horizons for each plot was then ground for chemical analysis. The collected composite mineral soil samples were air-dried, sieved with 2-mm mesh, and subjected to analyses for selected physicochemical properties. Soil texture was measured with a Fritsch GmbH Laser Particle Sizer ANALYSETTE 22 (Idar-Oberstein, Germany). The soil organic carbon (SOC), total nitrogen (TN), and total sulfur (TS) were analyzed with a LECO TruMac® CNS analyzer. The pH of the samples was measured in 1 M KCl solution (pH_{KCl}; soil/liquid ratio 1:5, w/v) with a digital pH meter at 20°C, and soil electrical conductivity (EC) (1:5 soil/solution ratio) was measured with a conductivity meter at 20°C with an accuracy of 1.0 μS cm^{-1}. To determine the bulk density (BD), soil samples were dried at 105°C for 48 h and then weighed. BD (g/cm^3) was calculated by dividing the mass of the oven-dried soil by the volume of its cylinder (Sumner, 2010). To estimate SOC and TN accumulated in the A horizon under succession in bare rock without applied topsoil, the weight of the layer was calculated from the average thickness of the layer and its bulk density; the weight of the layer was multiplied by the carbon content of the A horizon which was subtracted for the carbon content in the bare rock without vegetation, under the assumption that similar overburden spoils were on the surface when pedogenesis started under succession. This was used to correct data for the fossil organic carbon present in the dumped spoil material (Frouz et al., 2009; Reintam, 2004).

The SOC and TN stocks in the organic horizons were calculated with the following equations:

$$\mathrm{SOC_{stock}}\,(\mathrm{Oi+Oe})\left[\mathrm{Mg\,ha^{-1}}\right]=\mathrm{M}\,(\mathrm{Oi+Oe})\left[\mathrm{Mg\,ha^{-1}}\right]\times \mathrm{C}\,[\%]/100, \tag{1}$$

$$\mathrm{TN_{stock}}\,(\mathrm{Oi+Oe})\left[\mathrm{Mg\,ha^{-1}}\right]=\mathrm{M}\,(\mathrm{Oi+Oe})\left[\mathrm{Mg\,ha^{-1}}\right]\times \mathrm{N}\,[\%]/100, \tag{2}$$

where SOC_{stock} (Oi + Oe) and TN_{stock} (Oi + Oe) are the soil organic carbon and the total nitrogen stock, respectively, in the organic horizons, M (Oi + Oe) is the dry mass of the organic horizons, and C and N are the carbon and nitrogen content, respectively, in the Oi + Oe horizons.

The SOC and TN stocks in the mineral horizons were calculated with the following equations:

$$SOC_{stock}\,(0-10\,cm)\,\left[Mg\,ha^{-1}\right] = C\,[\%] \times BD\,\left[g\,cm^{-3}\right] \times D\,[cm], \quad (3)$$

$$TN_{stock}\,(0-10\,cm)\,\left[Mg\,ha^{-1}\right] = N\,[\%] \times BD\,\left[g\,cm^{-3}\right] \times D\,[cm], \quad (4)$$

where SOC_{stock} (0–10 cm) and TN_{stock} (0–10 cm) are the soil organic carbon and total nitrogen stock, respectively, in the 0–10 cm soil horizons, C and N are the carbon and nitrogen content, respectively, in the mineral horizon; BD is the bulk density of the fine fraction (<2 mm), and D is the depth (10 cm) of the mineral soil layer.

2.3 | Statistical analysis

A two-way analysis of variance (ANOVA) was used to investigate the effects of vegetation types and reclamation technologies on SOC, TN, and carbon and nitrogen stoichiometry. The mean, standard deviations, and Tukey's honestly significant difference (HSD) were computed. Before the analysis, the datasets were checked for normality using the Kolmogorov–Smirnov test. Statistica 13.3 (StatSoft, Inc., 2014) software was used to conduct the statistical analyses. All means were considered different when $p < 0.05$. The correlations between the studied basic soil properties and SOC and TN were described using Pearson's correlation matrix.

3 | RESULTS

3.1 | Soil physical and chemical properties

According to the widely used USDA soil texture classification (García-Gaines & Frankenstein, 2015), the soil under bare rock succession without topsoil (BRS) under different vegetation types belongs to the sandy loam texture class. In contrast, the topsoil reclaimed layer (topsoil cultivation [TSC] and topsoil succession [TSS]) has a loamy texture (Table 1).

According to USDA guidelines, BRS was classified as very strongly acidic to strongly acidic compared to TSC and TSS. BD was slightly higher in woodland than in forbland and grassland. On BRS, EC was higher in forbland than in woodland. Due to the higher geogenic carbon content in carboniferous rock, the highest SOCt, TN, and S were observed on BRS under all vegetation types compared to TSC and TSS (Table 1).

3.2 | The effect of reclamation and vegetation type on soil organic carbon and nitrogen stocks

The vegetation type and reclamation treatment had a significant impact on SOC and TN. However, the effects varied among soil

TABLE 1 Soil properties under three vegetation types and reclamation treatments at the post-mining site.

Vegetation type and reclamation	Horizon	SOCt ($g\ kg^{-1}$)	TN ($g\ kg^{-1}$)	TS ($g\ kg^{-1}$)	pH	EC ($\mu S\ cm^{-1}$)	BD ($g\ cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)
WL_TSC	Oe + Oi	415.9 ± 50	17.3 ± 4.1	1.3 ± 0.2	5.9 ± 0.4					
	A	35 ± 18.7	1.6 ± 0.6	0.2 ± 0.1	7.3 ± 0.3	205.7 ± 37.9	1.4 ± 0.2	51 ± 14	40 ± 12	9 ± 2
WL_TSS	Oe + Oi	372.0 ± 28.5	11.6 ± 2.2	1.2 ± 0.1	6.3 ± 0.2					
	A	12.7 ± 5.3	0.6 ± 0.2	0.1 ± 0.1	6.7 ± 0.7	163.9 ± 74.2	1.5 ± 0.1	41 ± 6	49 ± 6	10 ± 2
WL_BRS	Oe + Oi	466.8 ± 17.9	12.3 ± 1.5	1.4 ± 0.1	5.4 ± 0.4					
	A	114 ± 21.9	3.1 ± 0.5	2.9 ± 1.1	4.7 ± 0.9	107 ± 47.6	1.2 ± 0.2	60 ± 12	30 ± 8	10 ± 4
FL_TSC	Oe + Oi	452.6 ± 23.3	10.4 ± 2.6	1.3 ± 0.4	5.8 ± 0.4					
	A	32.2 ± 30.8	1.4 ± 0.6	0.8 ± 1.8	7.0 ± 0.7	181.8 ± 59	1.3 ± 0.2	56 ± 17	37 ± 15	7 ± 3
FL_TSS	Oe + Oi	427.6 ± 58.1	6.1 ± 2.1	1.1 ± 0.2	5.1 ± 0.6					
	A	29.1 ± 11.0	1.4 ± 0.4	0.3 ± 0.2	6.9 ± 0.4	236.6 ± 55.7	1.3 ± 0.1	49 ± 18	44 ± 16	7 ± 2
FL_BRS	Oe + Oi	463.1 ± 12	9.3 ± 2.9	1.3 ± 0.3	5.2 ± 0.4					
	A	122.3 ± 22.5	3.4 ± 0.7	5.4 ± 3.7	5.3 ± 1.0	269 ± 173	1.1 ± 0.1	62 ± 9	30 ± 7	8 ± 3
GL_TSC	Oe + Oi	439.5 ± 19.7	10.4 ± 1.9	1.4 ± 0.2	5.5 ± 0.3					
	A	31.5 ± 17.3	1.5 ± 0.6	0.5 ± 0.8	7.3 ± 0.4	211.8 ± 60.7	1.4 ± 0.2	44 ± 12	47 ± 11	9 ± 2
GL_TSS	Oe + Oi	428.2 ± 14.6	8.6 ± 1.6	1.3 ± 0.2	4.9 ± 0.3					
	A	40.6 ± 30	1.6 ± 0.8	0.8 ± 0.9	6.4 ± 1.2	168.2 ± 69.2	1.3 ± 0.2	48 ± 16	43 ± 14	9 ± 3
GL_BRS	Oe + Oi	429.7 ± 29.5	9.6 ± 1.4	1.5 ± 0.3	4.7 ± 0.6					
	A	126.1 ± 33.1	3.3 ± 0.6	3.2 ± 1.6	5.2 ± 1.3	122.1 ± 57.2	1.2 ± 0.2	56 ± 20	34 ± 15	10 ± 5

Note: Data are presented as mean ± SD; WL: Woodland; FL: Forbland; GL: Grassland; TSC: Topsoil cultivation; TSS: Topsoil succession; BRS: Bare rock succession.

Abbreviations: BD, bulk density; BRS, bare rock succession; EC, electrical conductivity; SOC, soil organic carbon; TN, total nitrogen; TS, total sulfur; TSC, topsoil cultivation; TSS, topsoil succession.

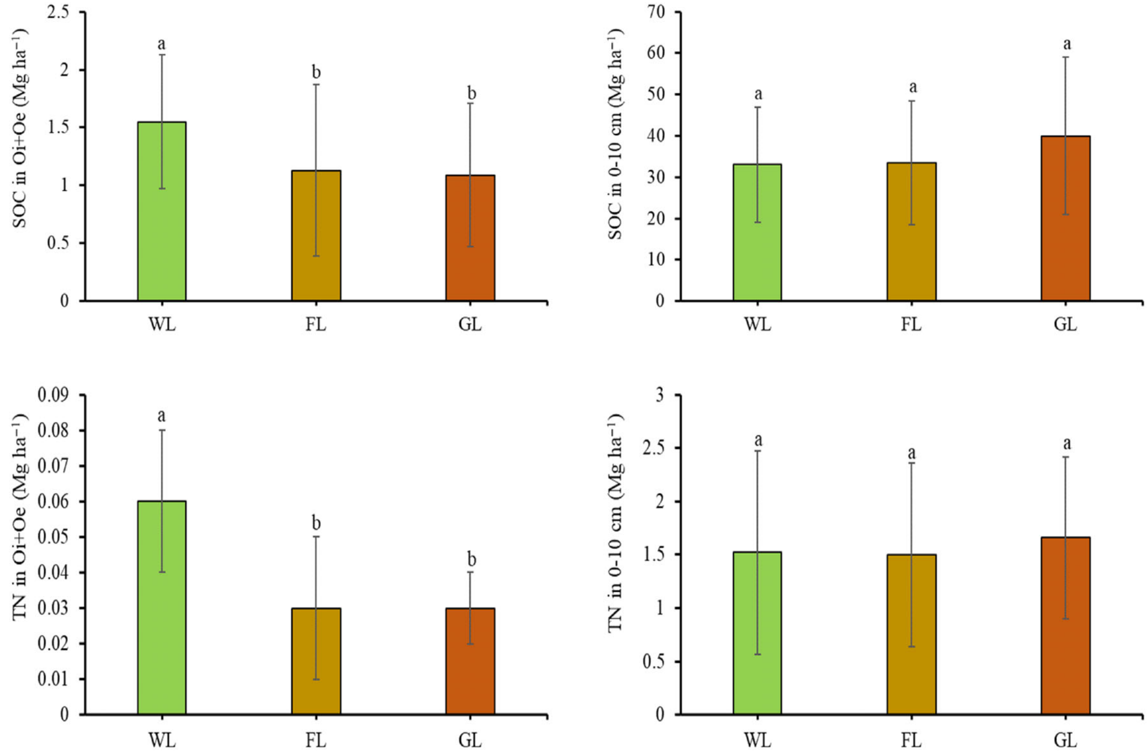

FIGURE 2 The effect of vegetation type on soil organic carbon (SOC) and total nitrogen (TN) stocks; FL, Forbland; GL, Grassland; WL, Woodland; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

horizons, that is, vegetation type playing a crucial role in the litter layer and reclamation at a depth of 0–10 cm. Soils under woodland exhibited higher SOC stock and TN stock in Oi + Oe compared to soils under forbland and grassland. There was no significant difference in SOC stock and TN stock at a depth of 0–10 cm among the vegetation types, except for higher values under grassland (Figure 2). The application of topsoil led to significantly higher SOC and TN stocks in the 0–10 cm soil (Figure 3).

Reclamation resulted in a significant change in SOC and TN stocks. Under woodland, the amount of SOC stock in the Oi + Oe was significantly higher after succession on bare rock compared to succession and cultivation on applied topsoil. This phenomenon (greater SOC stock under succession on bare rock than on applied topsoil) did not occur under grassland and forbland (Figures 4–6). However, reclamation did not significantly affect TN stock in Oi + Oe under all vegetation types.

The application of topsoil and cultivation resulted in a significant increase in SOC stock at a depth of 0–10 cm under woodland and forbland, while no effect was observed under grassland (Figures 4–6). Nevertheless, topsoil application and cultivation had a significant impact on TN stock under all vegetation types at the same depth (Figures 4–6). In woodland, the TN stock in 0–10 cm horizons was significantly higher under cultivation on topsoil compared to succession on topsoil and bare rock. Similarly, under forbland and grassland, TN stock was significantly higher under cultivation and succession on topsoil compared to succession on bare rock.

3.3 | Carbon and nitrogen stoichiometry

The organic layer had higher C:N ratios compared to the mineral soil horizons. In the Oi + Oe layer, forbland and grassland exhibited significantly higher C:N ratios than woodland. The highest values in the mineral horizons were found under all vegetation at BRS (Table 2).

3.4 | Relationship between SOC, TN, and basic soil parameters

The correlation analysis revealed that pH was positively correlated with SOC and TN. Clay had a positive correlation with TN, while sand had a negative correlation with TN (Table 3).

4 | DISCUSSION

4.1 | The effect of vegetation type on SOC and TN

Due to their functional roles, the vegetation types used for restoring mine spoil heaps have different effects on the SOC and TN. The higher SOC and TN values in the litter layer (Oi + Oe) under woodland than under grassland and forbland may be due to the increased litter production and decreased decomposition rates in woodland than in grassland and forbland (Zhang et al., 2016). McKenna et al. (2019)

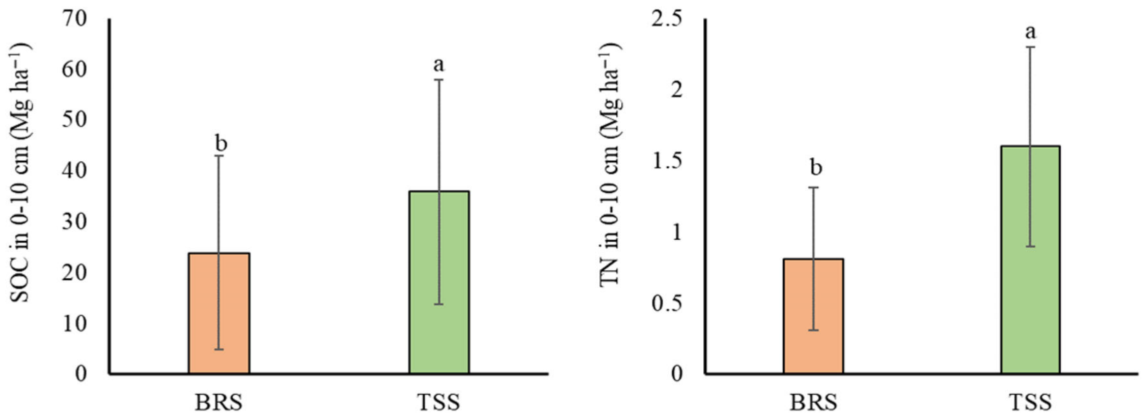

FIGURE 3 The effect of topsoil application on soil organic carbon (SOC) and total nitrogen (TN) stocks; BRS, Bare rock succession; RTS, Reclaimed topsoil succession; means followed by different letters (a, b) are significantly different from each other at p <0.05. [Colour figure can be viewed at wileyonlinelibrary.com]

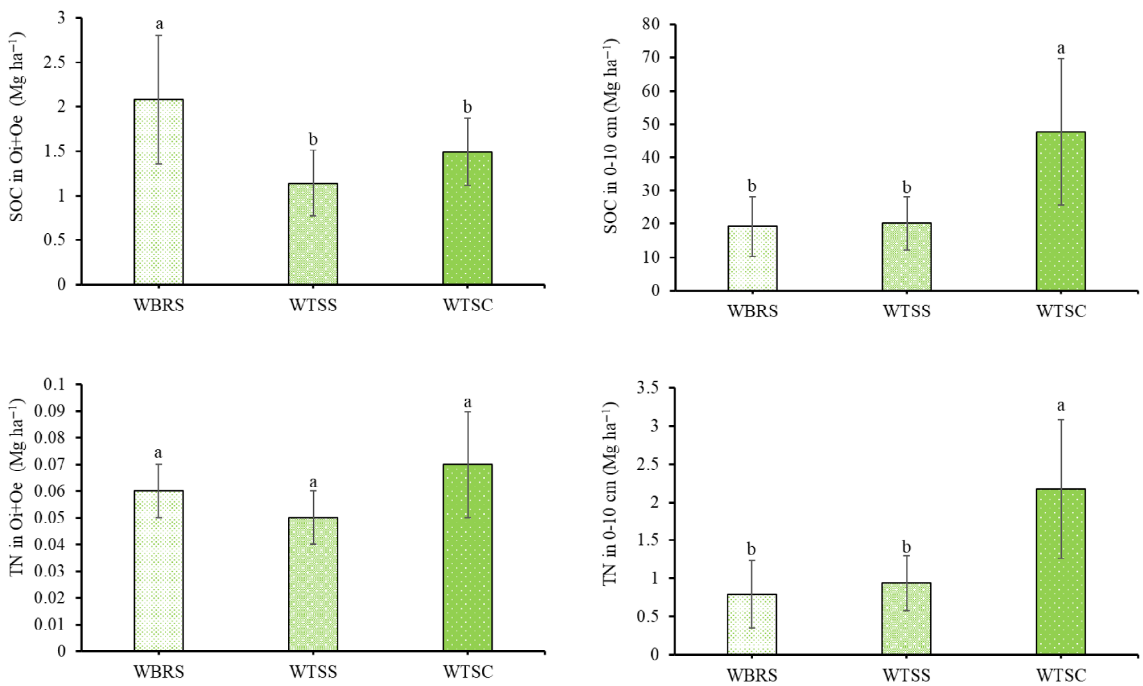

FIGURE 4 The effect of reclamation techniques on soil organic carbon (SOC) and total nitrogen (TN) stocks; WBRS, Woodland on bare rock succession; WTSS, Woodland on topsoil succession; WTSC, Woodland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at p <0.05. [Colour figure can be viewed at wileyonlinelibrary.com]

also observed significantly higher litter cover in open woodland than in grassland at a rehabilitated mine site, and Williams et al. (2012) found that woodland sites had more leaf litter and woody debris cover than pasture sites.

There was no significant difference in the SOC and TN stocks in the mineral horizons under different vegetation types. This could be due to the short restoration period (Kumar et al., 2018) as vegetation first affects the organic layer through litter deposition, and changes in the mineral soil occur through decomposition later. However, soils under grasslands tended to have greater SOC and TN stocks in the uppermost mine soil layers (A horizon) than soils under woodland and forbland. This is due to rapid litter inputs and fine root turnover in grasslands (Zhang et al., 2016). Generally, the primary source of SOC in grassland is the input of root residues due to grasses' extensive fine root systems (Nickels & Prescott, 2021; Wei et al., 2012). In the early restoration stage, grasslands accumulate more SOC than forests by allocating large amounts of carbon to the soil (Chatterjee et al., 2009; Shrestha & Lal, 2010). Likewise, Sperow (2006) and Zhang et al. (2020) observed the highest SOC and TN values under grassland and suggested that grasslands foster SOC and TN accumulation in reclaimed sites better than woodlands.

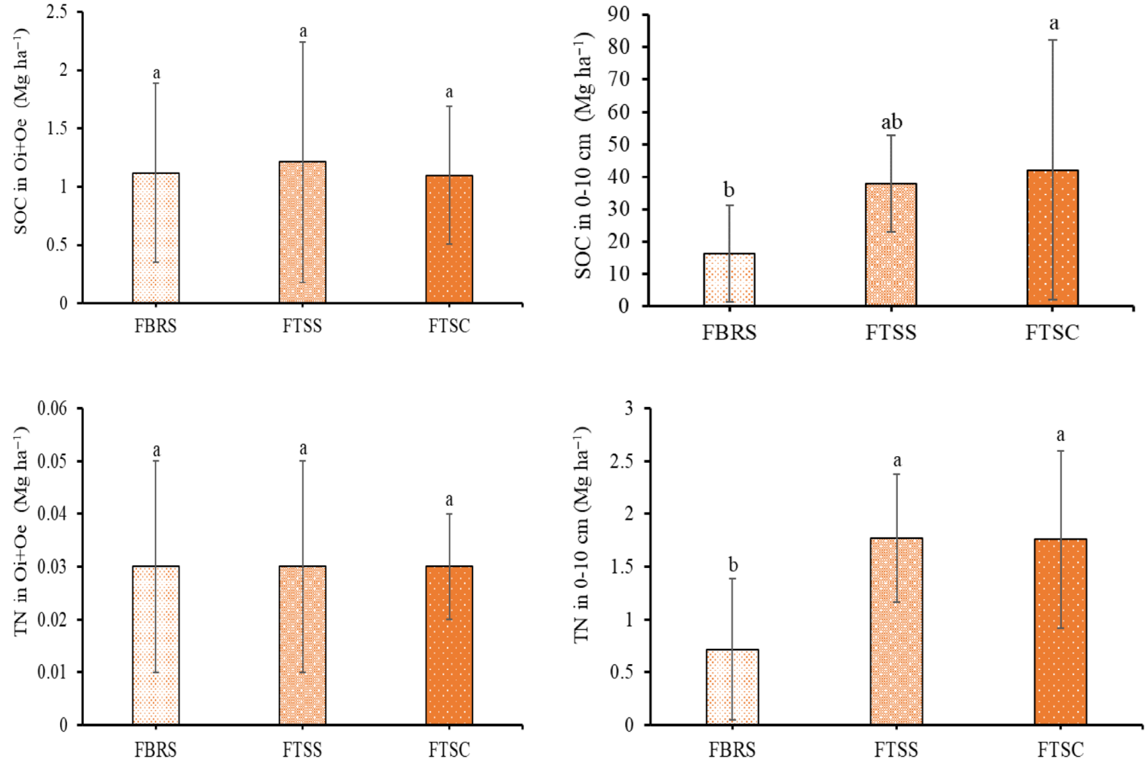

FIGURE 5 The effect of reclamation techniques on soil organic carbon (SOC) and total nitrogen (TN) stocks; FBRS, Forbland on bare rock succession; FTSS, Forbland on topsoil succession; FTSC, Forbland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

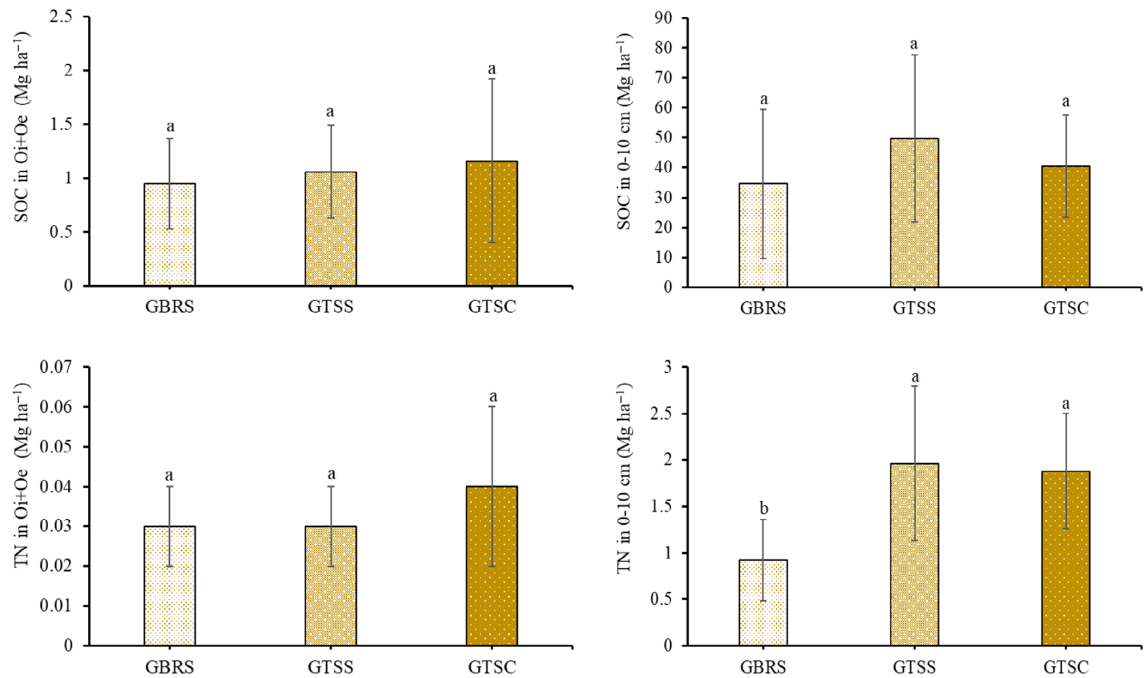

FIGURE 6 The effect of reclamation techniques on soil organic carbon (SOC) and total nitrogen (TN) stocks; GBRS, Grassland on bare rock succession; GTSS, Grassland on topsoil succession; GTSC, Grassland on topsoil cultivation; means followed by different letters (a, b) are significantly different from each other at $p < 0.05$. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Carbon and nitrogen stoichiometry in soils under the influence of different vegetation and reclamation.

Reclamation	Vegetation	C:N	
		Oi + Oe	A horizon
TSC	Woodland	26±9b[a]	25 ± 11a
	Forbland	47 ± 13a	21 ± 8a
	Grassland	44 ± 9a	21 ± 6a
TSS	Woodland	33 ± 6b	21 ± 6a
	Forbland	81 ± 33a	21 ± 3a
	Grassland	51 ± 8ab	25 ± 6a
BRS	Woodland	38 ± 5a	37 ± 3a
	Forbland	54 ± 14a	36 ± 3a
	Grassland	46 ± 7a	39 ± 5a

Abbreviations: BRS, bare rock succession; TSC, topsoil cultivation; TSS, topsoil succession.
[a]Means followed by different lowercase (a, b) are significantly different (at p <0.05).

TABLE 3 Pearson correlations between soil organic carbon (SOC), total nitrogen (TN) content, and basic soil properties.

	SOC	TN
Sand	−0.11	−0.18*
Clay	0.12	0.23*
Silt	−0.01	−0.12
BD	0.02	0.09
pH	0.26*	0.39*

Note: * indicates a significant correlation at p < 0.05.
Abbreviation: BD, bulk density.

Additionally, the variation in the vertical distribution of SOC and TN stocks under different vegetation types indicates the source of the inputs that contribute to the accumulation of SOC and TN. In woodland, aboveground inputs predominate, while in grasslands, the main contributors are root residues and exudates (Zhang et al., 2016). This vertical variation also exists among different tree species due to their effects on the soil fauna communities that are vital for litter decomposition. For example, the soil environment under pine litter is relatively unfavorable for fast decomposition due to acidic reactions (Horodecki & Jagodziński, 2019). Woś et al. (2022) revealed that pine had a higher C_{stock} in the Oi + Oe horizons, whereas alder had the highest C_{stock} values in the 0–5 cm soil horizons at a post-mining site. Therefore, the appropriate selection of vegetation is critical to enhancing the accumulation of SOC and TN in post-mining sites to mitigate climate change.

4.2 | The effect of reclamation techniques on SOC and TN

Reclamation of mining heaps creates more suitable conditions for SOC accumulation, facilitating vegetation establishment by improving the physical and chemical properties of the soil substrate. In this study, applying topsoil and cultivation significantly increased SOC and TN stocks compared to succession on bare rock mineral soil (A horizon). This impact was more notable under woodland and forbland: it increased the SOC by 40% and 27%, respectively, and the TN by 36% and 41%, respectively. According to Akala and Lal (2001), Bartuška et al. (2015), and Čížková et al. (2018), mine site reclamation with topsoil application resulted in greater SOC and TN accumulation than reclamation without topsoil. Pietrzykowski and Krzaklewski (2007) also revealed that reclaimed mining soils had three times more SOC and five times more TN than successional soils.

The litter layer (Oi + Oe) SOC and TN stocks were not significantly affected by reclamation, except in woodlands. In woodlands, the highest values were recorded after succession without topsoil reclamation. This could be due to litter accumulation and less favorable conditions for decomposition by microorganism at an unreclaimed mining site (Oktavia et al., 2015). Bare overburden sites are initially devoid of soil fauna compared to reclaimed mining sites, and colonization takes time. For example, Frouz et al. (2008) observed that earthworm colonization on bare overburden took 20 years. In contrast, colonization in alder plantations on reclaimed sites was instantaneous due to seedling soils and rapid vegetation development (Frouz et al., 2001). Therefore, rapid fauna colonization in reclaimed sites aids decomposition and stabilizes SOM in mineral soils, potentially increasing SOC storage (Frouz, 2018). This indicates that SOC accumulation at unreclaimed sites is less stable and reclamation with topsoil helps to stabilize SOC at mining sites.

However, reclamation did not significantly affect SOC and TN stocks under grasslands in either layer, except for TN in the mineral horizon. This demonstrates grasses' diverse functional roles in rapidly colonizing and improving degraded mining sites (Kumari & Maiti, 2019). However, one study in the Czech Republic found significantly higher SOC in topsoil-reclaimed grassland than in unreclaimed grassland on opencast lignite heaps (Čížková et al., 2018). This finding could reflect the variation in topsoil and the types of vegetation in reclaimed (cultivated grasses and legumes) and unreclaimed sites (*Calamagrostis epigejos* (L.) Roth). According to this finding, if mining sites are restored using woodlands and forblands, topsoil reclamation is recommended to improve SOC accumulation, whereas grasslands accumulate the same amount of SOC with or without topsoil reclamation. Additionally, Wei et al. (2012) reported high SOC accumulation and deep distribution of recent SOC in grasslands compared to secondary forests on degraded soils in the Loess Plateau in China. Guidi et al. (2014) reported greater SOC stability under grassland than in adjacent forests in the Italian Alps. The cost of topsoil application at mining sites is high (Zhu et al., 2021); therefore, at mining sites, grasses followed by forbs are preferred for SOC accumulation.

The litter layer had a higher C:N ratio than the mineral horizons at the study sites due to its fresh and undecomposed carbon (Obrist et al., 2015). At both reclaimed and unreclaimed sites, the C:N ratio in the Oi + Oe layers followed this order: woodland < grassland < forbland. We found no significant differences in the C:N ratios of the mineral horizons under all vegetation types. This may be due to the short-term impact of organic matter on soil properties (Woś et al., 2022);

however, we did find relatively higher values under all vegetation types at unreclaimed sites due to the geogenic carbon in carboniferous rock.

5 | CONCLUSION

This study investigated the significant influence of vegetation types and reclamation methods on SOC and TN stock values in a post-coal-mine heap. Their effects were different in the litter layer and in the mineral horizons. Vegetation type played a significant role in the litter layer (Oi + Oe) and reclamation success at 0–10 cm deep. Compared to the other vegetation types, there was higher SOC and TN stocks in the litter layer under woodland. Reclamation with topsoil and cultivation resulted in the highest SOC and TN stock values in the uppermost mineral horizons under woodland and forbland compared to succession on bare coniferous rock without topsoil under the same vegetation. In grassland, topsoil application and cultivation did not significantly affect SOC_{stock}. The C:N ratios in the litter horizons increased in the following order in both reclaimed and unreclaimed sites: woodland < grassland < forbland. Woodland produced higher SOC_{stock} when topsoil was applied, while grassland produced the same amount with or without topsoil application.

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CONFLICT OF INTEREST STATEMENT

The authors declare that no known competing financial interests or personal relationships influenced the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Original Articles

Spatial estimation of soil organic carbon, total nitrogen, and soil water storage in reclaimed post-mining site based on remote sensing data

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A R T I C L E I N F O

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A B S T R A C T

The estimation of Soil Organic Carbon (SOC), Total Nitrogen (TN), and Soil Water Storage (SWS) is crucial in comprehending ecosystem services and environmental sustainability. It plays a crucial role in guiding sustainable restoration strategies and supporting the long-term health of post-mining sites. Remote sensing technology provides valuable tools for modelling and mapping soil properties in reclaimed post-mining sites efficiently and cost-effectively. This study aimed to utilize remote sensing data to estimate SOC, TN, and SWS in a reclaimed post-mining site. Field data was collected from 130 research plots to obtain reference data for SOC, TN, and SWS from the Sonica hard coal post-mine spoil heap. Remote sensing data were: airborne laser scanning (ALS) point clouds and Planets cope satellite imageries. Generalized Additive Models (GAM) were used to develop predictive models. Wall-to-wall predictions of analyzed variables were performed. The results identified topographic and remote sensing indicators that significantly influence SOC, TN, and SWS. Digital Terrain Model (DTM), aspect, and blue spectral band are variables that explain SOC storage, with a significant influence of DTM, ranging from −8 to 18 Mg ha^{-1}. TN was explained by DTM, Canopy Height Model (CHM), blue and Near Infrared (NIR) spectral bands, and Normalized Difference Vegetation Index (NDVI), mainly influenced by NIR and NDVI, ranging from −1.1 to 0.8 and −0.9 to 1.4 Mg ha^{-1}, respectively. The values of Topographic Wetness Index (TWI), aspect, CHM, blue and NIR spectral bands explained SWS, highlighting their importance in assessing soil water dynamics in post-mining landscapes, with TWI and CHM being particularly influential, ranging from −2 to 5.1 and −6 to 2 mm, respectively. However, caution is advised when predicting SOC and TN using remote sensing in post-mining sites due to geogenic carbon considerations.

1. Introduction

Mining activities, including excavation, grading, and soil compaction, significantly alter the physical, chemical, and biological properties of soils, particularly, leading to a reduction in soil organic carbon (SOC), total nitrogen (TN), and soil water storage (SWS, Shahriari et al., 2011; Falahatkar et al., 2014; Ajami et al., 2016; Cetin et al., 2023; Feng et al., 2019). Land use changes associated with mining can also have significant impacts on SOC and SWS due to a reduction in vegetation cover, which can decrease the input of organic matter into the soil (Macdonald et al., 2015; Fettle's et al., 2005). In addition, heavy machinery used in mining operations can cause soil compaction, which can reduce pore space and limit water infiltration (Keller et al., 2013; Indira et al., 2020). Compacted soil can also reduce the activity of soil microbes and the decomposition of organic matter, leading to a decline in SOC (Havaee et al., 2014; Reboot et al., 2018; Filcheva et al., 2021; Singh et al., 2022).

Minimizing the impact of mining activities requires crucial reclamation efforts, including the application of topsoil, enhancement of soil nutrient content, and the planting of suitable vegetation (Maiti et al., 2021; Gastauer et al., 2022). However, the differences in topographic factors, reclamation techniques, and vegetation types led to spatial and temporal differences in improving soil properties. The topography often changes due to mining activities, resulting in the formation of spoil heaps, waste rock dumps, and tailings storage facilities (Agboola et al., 2020; Lawrence et al., 2023). These disturbances can alter the soil properties and change the spatial distribution of SOC, TN, and SWS.

To enhance the effectiveness of reclamation strategies of post-mining sites, it is essential to comprehend the spatial distribution of these soil

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properties and model their behavior. Remotely sensed technologies provide valuable tools for modeling and mapping soil properties, such as SOC, TN, and SWS in reclaimed post-mining sites (Thaler et al., 2019; van Wesemael et al., 2023). They offer efficiency, cost-effectiveness, and the ability to map and monitor SOC, TN, and SWS over large areas.

Pilot studies have demonstrated the use of remote sensing for SOC and TN mapping in exposed croplands (Huang et al., 2022). This capability enables the monitoring of changes in SOC, TN, and SWS over time. The study on the spatial distribution of SOC in mining areas by Yang et al.(2022) in Shendong Mining, China, found that land use, followed by NDVI, precipitation, temperature, elevation, and mining intensity significantly influenced SOC levels. Reclamation practices can also impact soil properties in mining sites. The findings of different scholars reveal that soil amendments and vegetation planting significantly increased SOC and TN content (Pietrzykowski and Daniels, 2014; Frouz and Vindušková, 2018; Singh et al., 2022; Woś et al., 2022).

Several studies have shown the influence of topographic factors on these soil properties in post-mining sites. Zhang et al. (2019) conducted a study in a mining site and found that slope significantly influenced SOC levels. Steep slopes often result in erosion and the removal of topsoil, which can reduce SOC and water storage capacity (Mensah et al., 2015). Li et al. (2018) studied the effects of aspect on soil properties in a mining area and found that SOC content was higher on north-facing slopes. North-facing slopes tend to have more shade and retain more moisture, which can enhance SOC and water storage (Singh, 2018). Guo et al. (2022) revealed the increased SOC content with elevation. Higher elevations often have lower temperatures, which can slow down the decomposition of organic matter and increase SOC content (Munoz et al., 2015). However, all of these studies are limited to some parameters and exclude others that are also very crucial, so our research approaches in a holistic manner how different topographic elements affect SOC, TN, and SWS using satellite and field data.

In previous research, SWS was estimated (Misebo et al., 2023), and SOC and TN were determined using field-collected data. However, this paper introduces a novel approach by utilizing remote sensing data, with the previous field data serving as reference points for this study. This paper makes a significant contribution to the use of remote sensing data in modeling essential ecosystem functions in post-mining areas and identifies variables that affect ecosystem function for sustainable restoration of these areas. Thus, the objective of this study was to assess the feasibility of estimating SOC, TN, and SWS on reclaimed post-mining site, the Sośnica hard coal post-mine spoil heap, based on topographic indices derived from high-resolution Digital Terrain Model (DTM), Canopy Height Model (CHM) obtained from ALS point clouds, and spectral characteristics derived from high-resolution PlanetScope satellite images based on Generalized Additive Models (GAMs). We opted for the GAMs approach due to its flexibility, interpretability, and robustness. GAMs allow for the modeling of non-linear relationships through smooth functions, with each predictor contributing additively. This method enhances interpretability by providing clear visualizations of each predictor's impact on the response variable, in contrast to many black-box machine learning models. These qualities make GAMs a powerful tool for capturing complex data patterns while maintaining model transparency (Hastie and Tibshirani, 1990; Wood, 2011).

2. Materials and methods

2.1. Study site

The research was carried out in the southern region of Poland (Upper Silesian Voivodeship), specifically at the Sośnica hard coal post-mine spoil heap (50°27′ N, 18°74′ E) located in Gliwice and Zabrze (the nearest main city: Katowice), within the Upper Silesian Coal Basin (Fig. 1). This site experiences an average annual temperature of 8.5 °C and a mean annual precipitation of 727 mm (Misebo et al., 2023). For over 250 years, the site was utilized for extracting hard coal (Kompała-Bąba et al., 2021). The spoil heap deposits consist of carboniferous rocks, predominantly shale, sandstone, and conglomerates (Pietrzykowski & Krzaklewski, 2018). These deposits exhibit characteristics such as poor water retention, low content of soil organic matter (SOM) and nutrients, and a high presence of geogenic carbon (fossil; Cabała et al., 2004). Reclamation efforts involve shaping and leveling the surface, applying topsoil, and cultivating diverse tree species, forbs, and grasses. Partly the sites underwent passive reclamation through natural succession, with various vegetation types such as tree species, forbs, and grasses emerging on both the reclaimed topsoil and the unreclaimed mine spoils (Kompała-Bąba et al., 2019).

2.2. Soil sample collection and analysis

In October 2021, soil samples were gathered from a total of 130 research plots that were randomly established in a size of 10 × 10 m. Among these plots, 60 were designated for spontaneous succession, including forbland, grassland, and woodlands that had developed naturally from barren rock and through topsoiling (Jiang, 2021). Each variant within the spontaneous succession category had 10 replications. The other 60 plots were allocated on active reclamation (topsoil cultivation) with 10 replicates of each variant for bland (*Lupinus polyphyllus* and *Melilotus alba*), grassland (*Festuca ruba* and *Arrhenatherum elatius*), and woodlands (*Robinia pseudoacacia* and mixture of different species)

Fig. 1. The area of interest (AOI) Sośnica – location at the part of Europe and Poland.

based on dominancy and area coverage. 10 plots were established on the control site (topsoil without vegetation, Fig. 1).

Soil samples were collected in previous studies to estimate SWS (Misebo et al., 2023), and SOC and TN, serving as reference points for this study. Boreholes were dug in each plot using soil drills to collect the soil samples. From each plot, mixed samples weighing approximately 1.0 kg when fresh were collected from four points at the corners and one from the middle, all at a depth of 0–10 cm. Additionally, to determine soil water storage, intact soil samples were collected from the middle of each plot using 100 cm^3 cylinders, resulting in a total of 130 samples. The location of each sampling point was determined with sub-meter accuracy in RTK (Real Time Kinematic) mode using the HI-TARGET V30 GNSS GNSS receiver (Global Navigation Satellite Systems).

The collected soil samples were air dried to a constant weight at 65°C and passed through a 2 mm mesh sieve, then analyzed for SOC and TN using a LECO TruMac® CNS analyzer. For the assessment of SWS, undisturbed soil samples were weighed initially to determine the soil water content. These samples were then saturated through capillarity for 48 h and weighed again. Subsequently, the soil samples were dried at 105°c for 48 h and weighed once more. The laboratory results are presented in Table 1.

2.3. Calculation of potential explanatory variables

To reach the research goal different types of datasets were used, including: 1) aerial orthophotomaps: year of acquisition: 2019; RGB and CIR (Color Infrared) compositions; source: Main Office of Geodesy and Cartography, Poland (source: geoportal.gov.pl); 2) PlanetScope satellite imagery (Planet; Fig. 2) – acquisition date: 18.06.2021; four spectral bands: Blue, Green, Red, and NIR (near infrared). The constellation includes more than 150 nanosatellites and provides a unique dataset of Earth-based observations (Szostak et al., 2021); and 3) Airborne Laser Scanning (ALS) point clouds – a year of acquisition: 2019; density: 12 pts/m^2; source: Main Office of Geodesy and Cartography, Poland, (source: geoportal.gov.pl).

The aerial orthophotos were used for the identification of areas where the bare rock occurs. The vector polygon layer with the extent of bare rock was manually created based on on-screen photo interpretation. These areas were excluded from further analysis due to their higher geogenic carbon content, which could potentially impact the results and interpretation of carbon content in the reclaimed post-coal mining areas.

Planet Scope imagery and ALS data were used for the calculation of potential explanatory variables for predictive modeling. All single spectral bands of the PlanetScope image and normalized differential vegetation index (NDVI) calculated based on NIR and Red bands were used for the development of predictive models for SWS, SOC, and TN.

The ALS point clouds were processed using a lidR package for R (Roussel and Auty, 2022). In the first step, a Digital Terrain Model (DTM) with a spatial resolution of 1.0 m was created using the "grid_terrain" function. In the next step, several topographic variables were calculated based on the created DTM using the whitebox package for R (Lindsay, 2016), including slope (in degrees), aspect, and topographic wetness index (TWI). All calculated topographic variables were used in the further analysis as explanatory variables in predictive models. Additionally, the point clouds were normalized using the "normalize_height" function and "tin" algorithm and after that, a Canopy Height Model (CHM) with a spatial resolution of 1.0 m was created using the "grid_canopy" function with the "p2r algorithm".

Table 1
Descriptive statistics of measured values for SOC (Mg/ha), SWS (mm), and TN (Mg/ha), n = 130.

Category	Statistic	SOC	SWS	TN
CONTROL	mean	53.30	18.20	1.52
	SD	46.62	5.01	1.09
	min	10.09	10.24	0.37
	max	154.93	26.07	3.83
FORBLANDS	mean	34.57	20.44	1.50
	SD	33.49	6.60	0.87
	min	0.02	5.58	0.02
	max	208.78	32.81	4.50
GRASSLANDS	mean	41.28	22.55	1.66
	SD	23.03	6.43	0.76
	min	2.79	10.24	0.42
	max	103.70	33.88	3.51
WOODLANDS	mean	34.08	15.50	1.52
	SD	22.01	6.24	0.96
	min	2.51	3.66	0.15
	max	104.51	28.90	3.83
Overall	mean	39.93	19.39	1.56
	SD	28.76	6.89	0.88
	min	0.02	3.66	0.02
	max	208.78	33.88	4.50

SOC: soil organic carbon; SWS: soil water storage; TN: total nitrogen.

2.4. Predictive modeling

The Generalized Additive Model (GAM; Hastie and Tibshirani, 1990; Wood, 2017) approach was used for the development of predictive models for SOC, SWS, and TN. The models were developed using the mgcv package for R (Wood, 2011). The same set of explanatory variables was used for each target variable (SOC, SWS, and TN), and the automatic feature selection method available in the mgcv package was applied (parameter *select* = TRUE in the "gam" function). The Gaussian distribution with identity link function was used for model development. To evaluate the model performance, the following standard metrics were calculated using the yardstic package for R (Kuhn and Vaughan, 2022): Root Mean Squared Error (RMSE), relative RMSE (rRMSE = RMSE / mean of observed values × 100 %), Mean Absolute Error (MAE), relative MAE (rMAE = MAE / mean of observed values × 100 %) and coefficient of determination (R^2). Additionally, the partial effect plots were created to analyze the influence of predictor variables on the target variable. To visualize the spatial distribution of the analyzed variables the prediction in a 10 m square grid was performed.

3. Results

For the development of predictive models, the ten potential explanatory variables were used. Summary statistics of the predictors in four categories of training plots are presented in Table 2.

The metrics of accuracy of the developed GAM models for SWS, SOC, and TN based on various predictor variables area presented in Table 3. The worst model was obtained for SOC with R^2 = 0.15 and rMAE = 45.37 %. The highest R^2 was observed for TN (0.45), while the lowest rMAE was obtained for SWS (25.26 %). The observed vs predicted scatterplots (Fig. 3) showed that SOC model has a tendency to overestimation lower values and underestimation of high SOC values.

3.1. The effects of selected explanatory variables on SOC, SWS, and TN.

The storage of SOC was mainly influenced by elevation (DTM) and spectral reflectance in Blue band. A slight influence was also observed for Aspect. Based on the analysis of the partial effect plots (Fig. 4), it can be observed that among the variables selected by the model, DTM exerts the greatest influence on SOC, causing variations in SOC storage ranging from −8 to 18, assuming other variables are held at their mean values. For elevations up to around 250 m a.s.l. the elevation caused decrease in SOC, while for elevation above 250 m a.s.l. SOC slight increase of SOC (Fig. 4). Slightly higher SOC values were observed on northern aspects, while lower values were observed on southern aspects. An increase in spectral reflectance in Blue band values until reaching approx. 0.6 caused decrease of SOC storage; thereafter, very wide confidence intervals for effect of Blue band were observed (Fig. 4).

TWI, Aspect, CHM, Blue, and NIR all had an impact on SWS, as

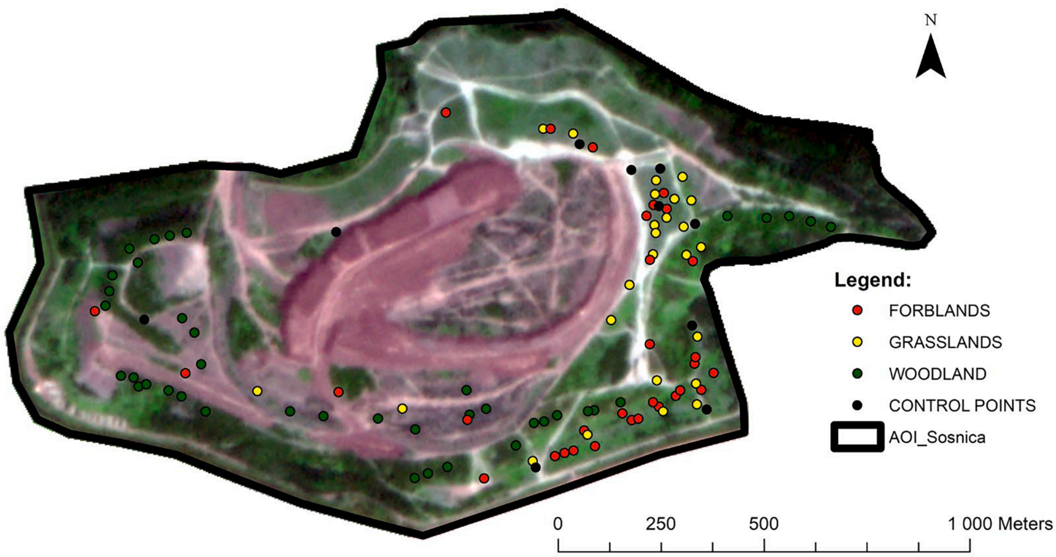

Fig. 2. PlanetScope (Planet) imagery masked to the study area (date:18/06/2021).

Table 2
Summary statistics of the predictors in four categories of training plots (n = 130).

		DTM	Aspect	Slope	TWI	CHM	Blue	Green	Red	NIR	NDVI
CONTROL	Mean	252.38	186.13	4.78	4.70	0.13	0.04	0.08	0.07	0.32	0.64
	SD	15.06	70.85	4.22	0.81	0.36	0.02	0.02	0.03	0.05	0.13
	Min	228.50	83.73	0.83	2.87	0.00	0.03	0.06	0.04	0.20	0.35
	Max	269.88	316.69	12.69	5.65	1.14	0.08	0.13	0.14	0.40	0.81
FORBLANDS	Mean	246.12	151.13	9.13	4.75	0.04	0.03	0.07	0.05	0.34	0.73
	SD	11.73	66.33	6.07	0.89	0.06	0.01	0.01	0.01	0.09	0.11
	Min	229.44	54.34	0.74	2.99	0.00	0.03	0.05	0.03	0.15	0.44
	Max	269.26	349.41	22.24	6.69	0.33	0.05	0.09	0.08	0.48	0.87
GRASSLANDS	Mean	250.84	159.48	7.38	4.99	0.05	0.04	0.07	0.06	0.33	0.68
	SD	12.51	50.17	7.68	1.55	0.12	0.01	0.01	0.02	0.07	0.12
	Min	231.41	48.43	0.64	2.27	0.00	0.02	0.06	0.03	0.19	0.40
	Max	269.62	248.89	29.89	12.01	0.73	0.07	0.12	0.12	0.48	0.86
WOODLAND	Mean	252.57	171.43	10.74	3.99	5.78	0.03	0.05	0.03	0.37	0.80
	SD	4.91	42.29	5.81	0.89	2.03	0.01	0.00	0.01	0.10	0.11
	Min	238.42	74.20	1.66	1.80	1.71	0.02	0.05	0.02	0.20	0.53
	Max	261.92	279.55	21.91	5.99	8.86	0.04	0.06	0.06	0.51	0.91

DTM: digital terrain model; TWI: topographic wetness index; CHM: canopy height model; NIR: near-infrared; NDVI: normalized difference vegetation index.

Table 3
Statistical Metric values for SOC, SWS, and TN.

Metric	SOC (Mg ha^{-1})	SWS (mm)	TN (Mg ha^{-1})
Root Mean Squared Error	26.62	5.8	0.65
Mean Absolute Error	17.21	4.9	0.49
Relative Root Mean Squared Error (%)	70.20	29.91	41.87
Relative Mean Absolute Error (%)	45.37	25.26	31.33
R^2	0.15	0.29	0.45

illustrated in Fig. 5. Higher values of TWI and NIR corresponded to an increase in SWS, while higher values of Blue were associated with a decrease in SWS. Higher SWS values were observed on northern aspects, while lower values were observed on southern aspects. The increased SWS was seen under a lower CHM (linked to grasses); it then decreased until CHM reached 2.5 m, after which it began to rise again, as depicted in Fig. 5. Among the variables, TWI and CHM exert a greater influence, causing variations in SWS ranging from −2 to 5.1 and −6 to 2, respectively, when other variables are held at their mean values.

Fig. 6 illustrates the impact of DTM, CHM, Blue, Green, NIR, and NDVI on TN. There is an inverse relationship between TN and both Blue and NDVI, as depicted in Fig. 6. TN exhibits a significant increase with higher values of CHM and NIR. Response plots demonstrate TN's fluctuation with DTM; there is a slight increase initially, followed by a decrease after 235 m, and then a subsequent increase above 250 m (Fig. 6). Among the variables, DTM, NIR, and NDVI exert a greater influence when other variables are held at their mean values.

3.2. *Spatial distribution of vegetation, SOC, TN, and SWS*

The spatial distribution of model predictions for SOC, SWS, and TN are presented in Fig. 7. The areas masked in black were excluded from the analysis as the bare rock was identified there.

4. Discussion

Remote sensing data provide precise and objective information about the surface and environment and give possibilities for novel spatial management and environmental protection. Using satellite imageries, UAV (Unmanned Aerial Vehicle) or LiDAR (Light Detection and Ranging) technology has a multitude of examples in research for post-industrial and reclaimed areas (Ai et al., 2020; Koska et al., 2017; Moudrý et al., 2019; Szostak et al., 2019, 2020; Szostak and Pająk, 2023; Urban et al., 2016). Remote sensed methods allow for large-scale

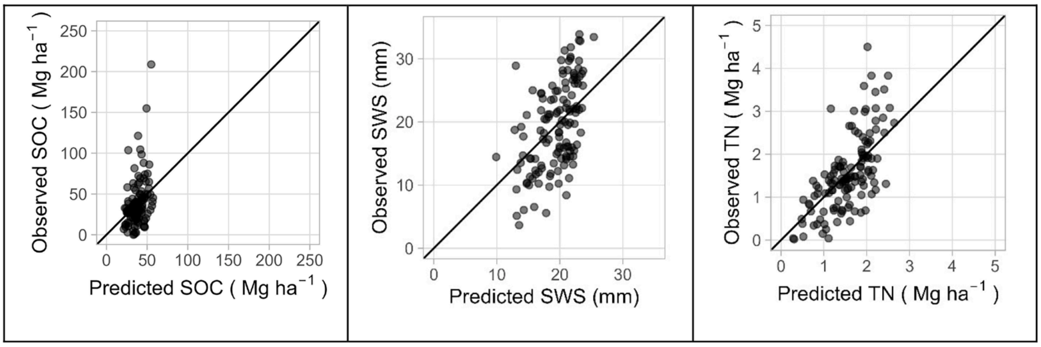

Fig. 3. Observed vs predicted values for soil organic carbon (SOC), soil water storage (SWS), and total nitrogen (TN).

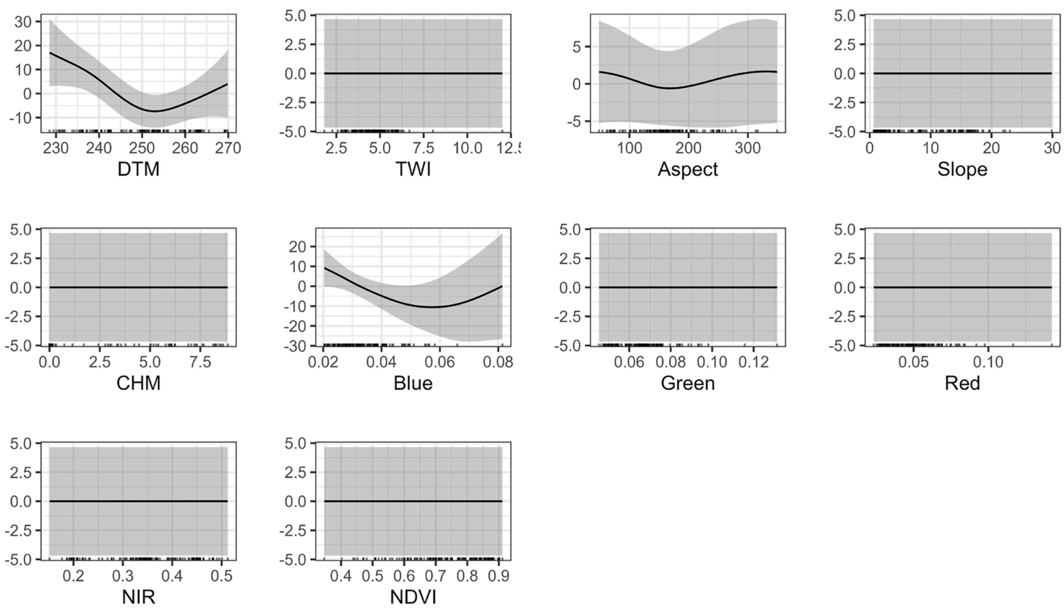

Fig. 4. Partial effect plots showing the influence of explanatory variables on SOC in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

research, especially topography description and structure of the growing vegetation (Asgari et al., 2020).

The GAM assisted in the identification of explanatory variables that affect the storage of SOC, TN, and SWS in the post-mining novel ecosystem. Among the variables, SOC storage is influenced by the Digital Terrain Model (DTM), Aspect, and Blue. SOC storage was higher at lower elevations and increased with rising DTM after 250 m, possibly due to higher temperatures at lower elevations that generally promote more rapid plant growth and microbial activity, resulting in higher rates of organic matter input and decomposition (Munoz et al., 2015). However, the slight increase in SOC with increasing elevation after 250 m may be due to reduced soil temperatures, which inhibit soil respiration, leading to a higher SOC stock (Tsui et al., 2013). Similarly, Guo et al. (2022) demonstrated an increase in SOC content with elevation.

The results also indicated that northern aspects had higher SOC storage, mainly because these slopes receive less direct sunlight, creating cooler and moister conditions that favor microbial activity, contributing to the preservation of organic carbon in the soil (Sharma et al., 2022). This finding aligns with Jakšić et al. (2021), who revealed that N- and NW-facing soils exhibited the highest levels of organic carbon in the topsoil.

Like SOC, the higher TN level was observed at lower elevations. However, the increase in TN with rising DTM after 250 m can be attributed to several factors. This increase is primarily linked to the prevalence of grass and nitrogen-fixing woody vegetation in higher elevations. These plant species contribute to the enrichment of nitrogen in the soil through their biological processes, enhancing the availability of nitrogen for plant uptake (Dollery et al., 2019). Additionally, the presence of a greater abundance of microorganisms in these areas plays a crucial role in facilitating the decomposition of organic matter and the fixation of nitrogen in the soil (Józefowska et al., 2023). The vegetation types with higher CHM and NIR values resulted in an increased amount of TN storage. As CHM and NIR increase, they indicate taller and denser vegetation, which leads to increased nutrient cycling and improved soil structure that promotes nitrogen accumulation in the soil (Zhang et al., 2020). Optimal revegetation patterns, such as woodlands, tend to have higher amounts of aboveground plant litter and soil organic matter compared to grasslands, resulting in greater total nitrogen levels (Pärtel et al., 2008). This highlights the potential of NIR and CHM as valuable tools for estimating TN levels in post-mining sites, similar to their effectiveness in natural environments. NIR spectroscopy, a technique used to analyze the composition of substances based on their interaction with near-infrared light, has shown strong correlations with key soil properties like SOC and TN (Pasquini, 2003). By utilizing NIR and CHM, researchers and land managers can efficiently assess TN levels, facilitating the restoration and management of post-mining landscapes.

However, vegetation with lower NDVI values had higher TN storage than with higher NDVI values. The higher values indicate woodland,

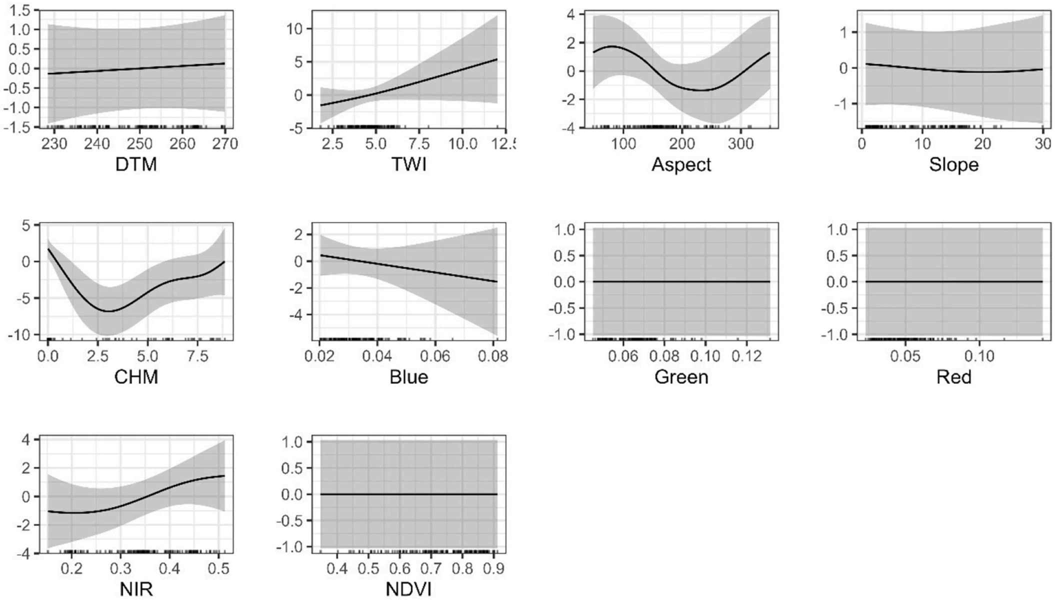

Fig. 5. Partial effect plots showing the influence of explanatory variables on SWS in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

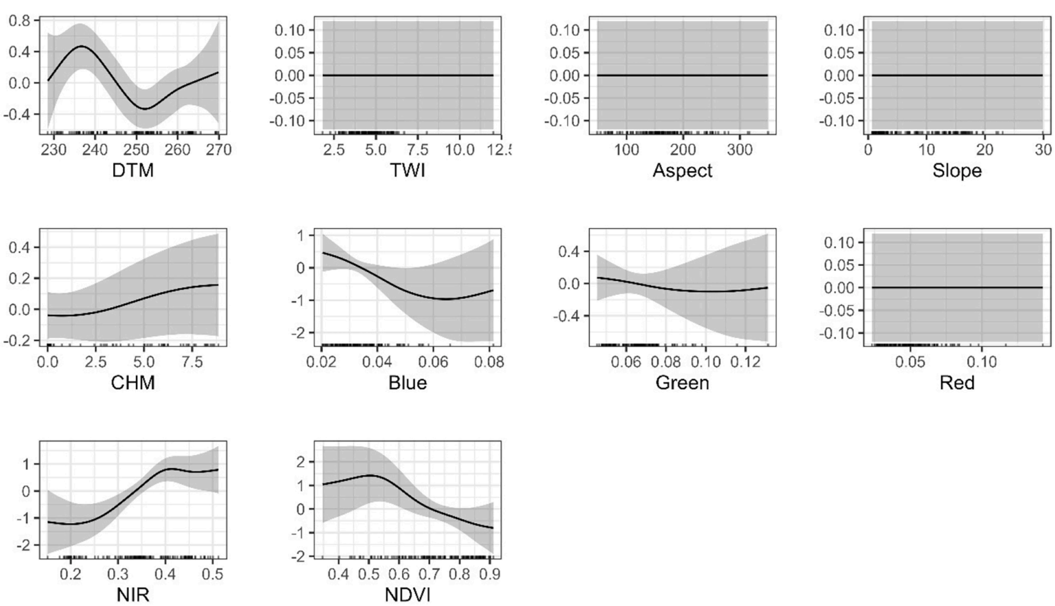

Fig. 6. Partial effect plots showing the influence of explanatory variables on TN in the study area. The y-axis represents the partial effect of each variable. The shaded areas indicate the 95% confidence intervals.

whereas the lower values indicate forbland and grassland (Brun et al., 2019; Table 2). NDVI values for grasslands, woodlands, and forblands can vary, and changes in these values can affect TN levels in a particular region. This finding revealed that the higher TN under forbland and grassland than woodland. The rapid influx of litter and turnover of fine roots in forblands and grasslands drive significant TN accumulation in the soil (Zhang et al., 2016). This is primarily attributed to the extensive fine root systems present in these ecosystems, which serve as the main source of SOC and TN (Wei et al., 2012; Nickels and Prescott, 2021). Similarly, Sperow (2006) and Zhang et al. (2020) noted that grasslands contribute to the highest TN values in reclaimed sites, suggesting that they foster better SOC and TN accumulation compared to woodlands.

The Topographic Wetness Index (TWI), CHM, Aspect, and NIR are identified as essential variables for determining SWS in post-mining sites. The higher water storage observed on north-facing slopes may be attributed to increased shade, enhancing SOC retention and moisture content (Singh, 2018). TWI serves as an indicator of soil moisture status derived from digital terrain data and shows a positive correlation with soil water storage (Haas, 2010). The higher TWI and NIR values correspond to increased SWS, underscoring the significance of TWI and NIR in assessing SWS in post-mining sites similar to natural environments.

Understanding the relationship between the Canopy Height Model (CHM) and SWS is crucial for comprehending ecosystem dynamics and hydrological processes in post-mining environments. Our model results indicate that vegetation with lower height, such as grasses, initially exhibits higher SWS but starts to increase after reaching 2.5 m. Field data suggests that SWS is higher under grassland and forbland, likely due to root distributions influencing key soil physical properties like

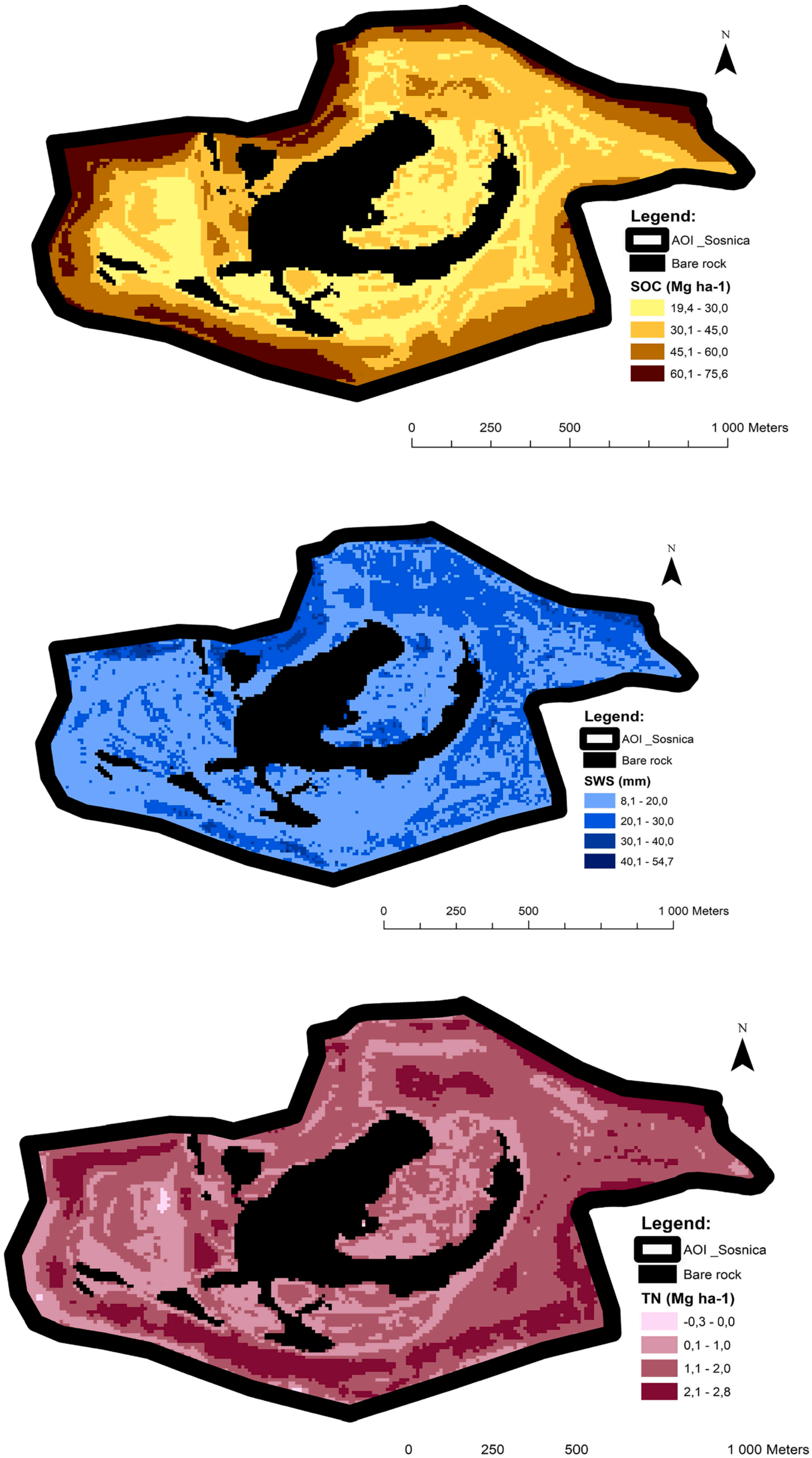

Fig. 7. Spatial distribution of soil organic carbon (SOC), soil water storage (SWS), and total nitrogen (TN) for the study area.

bulk density and porosity (Misebo et al., 2023).

The consistent positive correlation between CHM after 2.5 m and NIR, and SWS signifies that as NIR and CHM increase, denser and taller vegetation enhances water retention in the soil through improved structure and increased organic matter accumulation (Adrah et al., 2022). Taller canopies intercept more rainfall, reducing direct evaporation and facilitating greater water infiltration into the soil, thereby boosting soil water storage. The ability of planted vegetation to adapt to altered environments and influence crucial water-related soil properties significantly impacts soil water storage in post-mining sites. Therefore, it is imperative to focus on modeling SWS in post-mining sites utilizing CHM. Our comprehensive and multifaceted approach lays the foundation for using remote sensing data to estimate SOC, SWS, and TN in restored post-mining sites. By synthesizing different variables using a generalized additive model to identify factors influencing SOC, TN, and SWS in post-mining ecosystems, our research critically advances the understanding of the feasibility of remote sensing in predicting essential ecosystem services and identifies the most influential variables to be considered during restoration of post-mining sites. This methodological innovation, which incorporates remote sensing to model the variables affecting SOC, SWS, and TN in post-mining sites, fills a research gap not fully explored in previous studies and has the potential to greatly impact future ecosystem service modeling efforts. Based on this, we recommend future detailed studies on the role of remote sensing in estimating and modeling other important restoration quality indicator ecosystem services for better management of post-mining sites.

5. Conclusions

The integration of remote sensing data offers valuable insights into surface and environmental characteristics, facilitating enhanced spatial management and environmental protection strategies. Satellite imagery and airborne laser scanning have played pivotal roles in advancing research on post-industrial and reclaimed areas. The Generalized Additive Model (GAM) has been instrumental in identifying factors influencing SOC, TN, and SWS in post-mining ecosystems. Variables such as DTM, Aspect, and Blue significantly explain SOC storage, with DTM playing a crucial role. TN is influenced by DTM, CHM, Blue, NIR, and NDVI, particularly by NIR and NDVI. TWI, Aspect, CHM, Blue, and NIR values elucidate soil water storage dynamics, with TWI and CHM being notably influential. These findings highlight the importance of leveraging remote sensing technologies for a comprehensive understanding and effective management of post-mining ecosystems, fostering sustainable land use practices and environmental conservation efforts. However, caution is advised when utilizing remote sensing for predicting SOC in post-mining sites due to geogenic carbon considerations.

CRediT authorship contribution statement

Amisalu Milkias Misebo: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paweł Hawryło:** Writing – review & editing, Visualization, Methodology, Data curation, Conceptualization. **Marta Szostak:** Writing – review & editing, Visualization, Methodology, Data curation. **Marcin Pietrzykowski:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Research Article

Reclamation and vegetation effects on labile and stable soil organic carbon fractions in spoil heaps of coal mining waste

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ABSTRACT

Restoration of post-mining sites is essential to address soil degradation while providing critical insights into soil development, nutrient storage and carbon sequestration potential. However, field data remain inadequate to evaluate the combined effects of reclamation methods and vegetation types on soil organic carbon (SOC) fractions under specific site conditions. This study investigates the effects of reclamation methods and vegetation types on SOC fractions (free light fraction (C_{fLF}), occluded light fraction (C_{oLF}), and highly stable mineral-associated fraction (C_{MAF})), with a focus on strategies that promote SOC stabilization and improve ecological dynamics in post-mining soils on hard coal mine spoil heaps. Soil samples (0--10 cm and 10--20 cm) were collected for physical and chemical analyses from active restoration treatments (topsoiling and cultivation) and passive restoration treatments (succession on bare rock). The result showed that SOC fractions are significantly related to vegetation type and reclamation method. Succession on bare rock (SBR) resulted in a higher C_{fLF} content at a depth of 0--10 cm, whereas reclaimed sites with topsoil (RTS) exhibited significantly greater contents of C_{oLF} at both depths. Furthermore, C_{MAF} showed variation with reclamation method and depth, with the RTS site displaying a greater C_{MAF} in the surface layer but a lower C_{MAF} in the sublayer than the SBR site. Grassland vegetation exhibited significantly higher C_{fLF} (77%) in the 10-20 cm depth, C_{oLF} at 40.5% in the 0--10 cm depth and 56% in the 10--20 cm depth, C_{MAF} of 46.5% in the 10-20 cm depth compared to woodland. Forbland also exhibited significantly greater C_{oLF} (53%) in the 10-20 cm depth than woodland. In summary, the use of grassland vegetation and topsoil application effectively increases the SOC accumulation of all fractions in both soil depths, making it a beneficial approach for post-mining restoration strategies.

Key words: hard coal, postmining, reclamation, restoration, succession, topsoiling

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INTRODUCTION

Coal mining exerts significant impacts on ecosystems and landscapes, leading to extensive forest degradation and irreversible terrain alterations (Xiao *et al*., 2020; Chatterjee, 2021; Pietrzykowski *et al*., 2021). The process generates mine wastes and overburdens characterized by nutrient deficiencies, higher concentrations of heavy metals, a lack of fresh organic matter from plant litterfall, soil compaction, and impaired soil-water dynamics (Macdonald *et al*., 2015; Ahirwal & Maiti, 2017; Feng *et al*., 2019). These adverse conditions hinder plant growth and contribute to greenhouse gas emissions, exacerbating global climate change (Habib & Khan, 2021; Rouhani *et al*., 2023; Talukder *et al*., 2023). Consequently, reclamation of these overburdens is essential to restore post-mining sites to functional and sustainable states. Reclamation strategies include slope stabilization, topsoiling, and revegetation with suitable plant species (Maiti *et al*., 2021; Gastauer *et al*., 2022). However, the process is costly, and the availability of fertile substrates is often limited (Gunathunga *et al*., 2023). As a result, efforts are underway to leverage natural vegetation succession to reduce reclamation costs and foster the development of resilient, self-sustaining ecosystems over time. Nevertheless, this approach is time-consuming, and plant communities may become vulnerable to invasive species or the establishment of less desirable vegetation (Hapsari *et al*., 2020; Neto *et al*., 2021).

Reclaimed mining sites (RMSs) serve as potential reservoirs for soil nutrient storage as soils develop, offering a unique opportunity to observe soil development processes (Yuan *et al*., 2018). Evaluating the effectiveness of reclamation methods is critical for assessing the rate of ecosystem recovery. Among various soil properties, the accumulation rate of SOC is a key indicator of successful reclamation of mining spoil heaps (Kumar *et al*., 2018; Mukhopadhyay *et al*., 2016; Bandyopadhyay *et al*., 2020). SOC plays a vital role in nutrient cycling, carbon sequestration, and ecosystem stability, contributing significantly to the health and functionality of newly restored ecosystems on mining spoil heaps (Misebo *et al*., 2022; Yu *et al*., 2024). Several factors at mining sites, including physical disturbances such as excavation, topsoil removal, soil compaction, chemical contamination, and alterations in microbial communities, significantly influence SOC storage (Pietrzykowski *et al*., 2021; Cetin *et al*., 2023).

Reclamation using diverse tree species and topsoiling can accelerate the recovery of SOC (Kumar *et al*., 2015; Maiti & Ahirwal, 2019; Mei *et al*., 2024). SOC accumulation results from a balance between inputs—such as dead plant material, root and microbial exudates, and soil organism necromass—and losses through microbial respiration, leaching, and erosion (Basile-Doelsch *et al*., 2020). The dynamics of SOC accumulation are influenced by the diverse range of SOC fractions, each exhibiting distinct residence times and responses to environmental factors, including climate and land use (Gross & Harrison, 2019). Labile or free light SOC fractions, characterized by short residence times, respond rapidly to changes in climate or land use, whereas stable SOC fractions, with longer residence times, exhibit slower responses (Fontaine *et al*., 2007; Gruba *et al*., 2015; Soucémarianadin *et al*., 2018). These differences arise primarily due to biological, environmental, and physicochemical constraints on decomposition processes (Dynarski *et al*., 2020). Numerous studies indicate that specific reclamation methods and plant species are more effective than others in stabilizing SOC within mineral soils (Vesterdal *et al*., 2013; Gurmesa *et al*., 2013; Das & Maiti, 2016; Nickels & Prescott, 2021).

Preserving SOC is critical for maintaining essential ecosystem functions and mitigating global challenges like climate change (Taylor *et al*., 2021; Khan *et al*., 2021). Key mechanisms, including occlusion within soil aggregates and sorption onto mineral surfaces, protect SOC by restricting access to decomposers and enzymes, thereby promoting long-term carbon storage in soils (Gruba *et al*., 2015; Basile-Doelsch *et al*., 2020). Understanding the distribution of SOC fractions—such as the free light fraction (C_{fLF}), occluded light fraction (C_{oLF}), and mineral-associated fraction (C_{MAF})—provides critical insights into carbon dynamics. This knowledge enables the identification of targeted restoration strategies that enhance carbon stabilization and promote ecosystem recovery. Previous studies have highlighted the differential effects of vegetation and reclamation practices on labile and stable SOC fractions in reclaimed coal mine sites. Wick and Daniels (2009) found that grasses and forbs were more effective than forest communities in promoting particulate organic matter (POM) accumulation, with significant increases in protected organic matter within aggregates between 5-7 and 16-20 years after reclamation. Yuan *et al*. (2018) demonstrated that reclamation increased labile carbon fractions over time. Angst *et al*. (2018) further showed that plant-derived inputs primarily contribute to labile or intermediately stabilized soil organic matter (SOM) pools, while salvaged topsoil significantly enhances SOM stability, with the most stable fraction containing 26% more carbon compared to overburden-restored sites. Woś *et al*. (2023) highlighted the differential influence of tree species on labile carbon fractions in post-mining soils, with higher labile carbon values observed under alder compared to birch and pine. However, most previous studies RMSs have primarily focused on the labile SOC fraction, leaving a significant gap in understanding the combined effects of reclamation measures and plant functional groups on both labile and stable SOC fractions in post-mining areas.

Thus, the aim of this study was to assess how different vegetation types and reclamation methods influence SOC fractions at coal postmining sites to provide information beyond total SOC measurements and enhance the understanding of ecological dynamics. We hypothesize that the fractions of SOC in a reclaimed postmining site are primarily determined by the specific reclamation methods and vegetation functional groups established, as these methods influence soil properties and the vegetation contributes distinct organic matter inputs, both of which are crucial in shaping SOC composition and stability.

MATERIALS AND METHODS

Study site

The research was carried out in the southern part of Poland at the Sośnica hard coal postmining spoil heap located in Gliwice and Zabrze, within the Upper Silesian Coal Basin (50º 16' 22" N, 18º 44' 43" E). This site has an average annual temperature of 8.5 °C and receives an average annual precipitation of 727 mm. The site, which was a coal mine for over 250 years, covers approximately 170 acres and contains over 30 meters of overburden consisting primarily of Carboniferous rocks including shale, sandstone and conglomerate. (Kompała-Bąba *et al*., 2021). These deposits have poor water retention, low soil organic matter (SOM) content, limited nutrient availability, and high geogenic carbon (fossil) concentration (Cabała *et al*., 2004; Misebo *et al*., 2023).

Reclamation activities at the site included surface grading and leveling, application of approximately 50 cm of topsoil, and establishment of various tree species, forbs, and grasses. The reclaimed topsoil and unreclaimed mine spoils include a succession of different vegetation types (Kompała-Bąba *et al*., 2019). Age of all sites ranged from 20 to 25 years. The study area was revegetated with various plant species, including *Arrhenatherum elatius, Chamaenerion palustre, Calamagrostis epigejos, Festuca rubra, Solidago gigantea, Daucus carota, Melilotus alba, Populus tremula, Pinus sylvestris, Betula pendula, Alnus glutinosa, Salix alba, Robinia pseudoacacia,* and *Padus serotina,* as well as different *Populus* hybrids and *Populus nigra*.

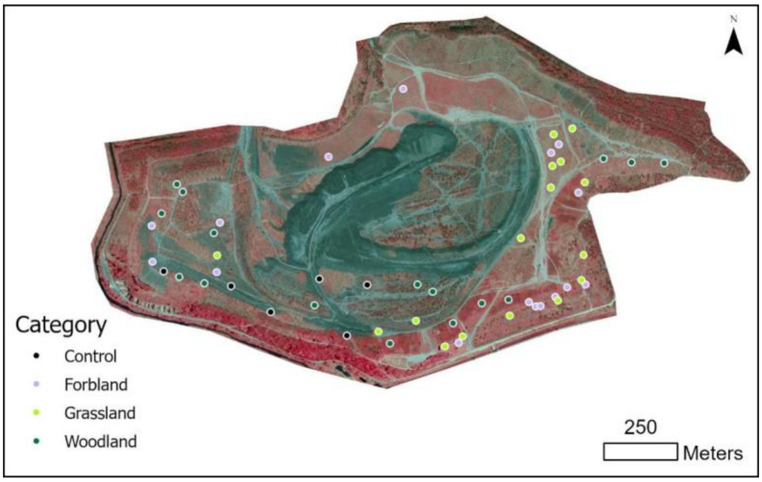


Fig. 1 Map of the study site.

TABLE I

Description of site categories. SBR: succession on bare rock; STS: succession on topsoil; CTS: cultivation on topsoil; WSBR: woodland succession on bare rock; WSTS: woodland succession on topsoiling; WCTS: woodland cultivation on topsoiling; GSBR: grassland succession on bare rock; GSTS: grassland succession on topsoiling; GCTS: grassland cultivation on topsoiling; FSBR: forbland succession on bare rock; FSTS: forbland succession on topsoiling; FCTS: forbland cultivation on topsoiling; C: control

	Variants			
	SBR	STS	CTS	Control
Reclamation method	Bare rock overburden material	Topsoiling	Topsoiling	Recent bare rock overburden material without vegetation (for geogenic carbon correction)
Vegetation management	Natural succession	Natural succession	Cultivation (afforestation)	
Vegetation types	Woodland, grassland and forbland	Woodland, grassland and forbland	Woodland, grassland and forbland	
Study variants	WSBR,GSBR and FSBR	WSTS,GSTS and FSTS	WCTS,GCTS and FCTS	C

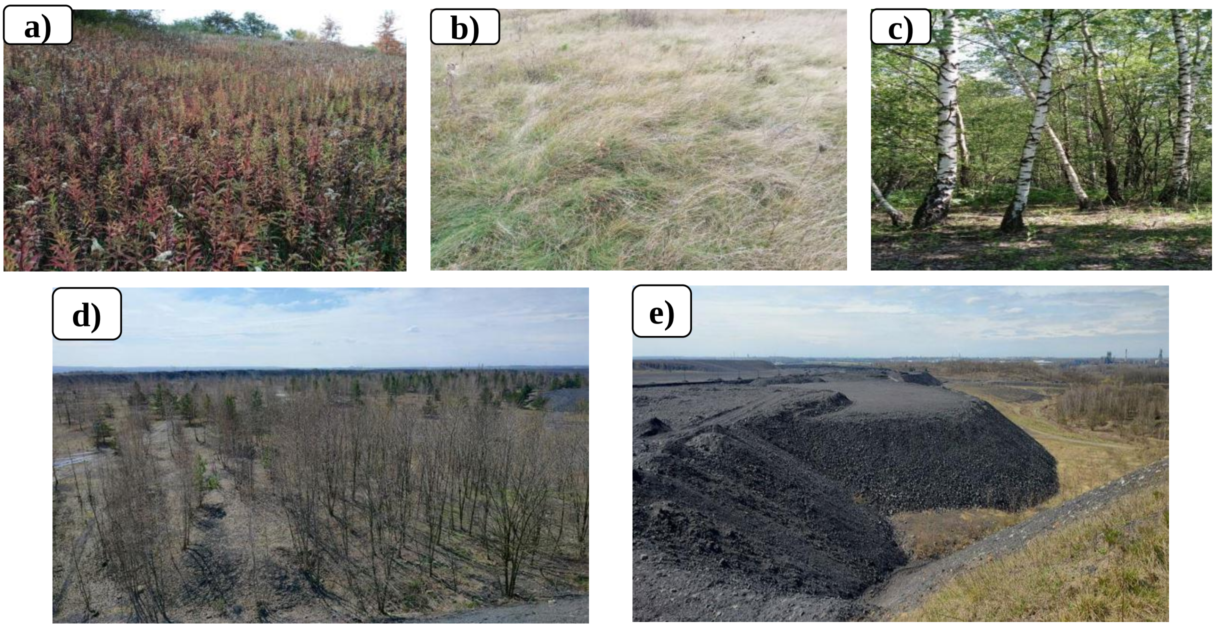


Fig. 2 Picture of vegetation types developed on the study mining heap; a), forbland b) grassland c) woodland on applied topsoil, d) woodland on bare rock succession, e) control, bare rock without vegetation (photo by A.M. Misebo).

Soil sampling and laboratory analyses

Soil samples were collected in October 2021 from sites undergoing restoration with various vegetation types (woodland, grassland, and forbland) and various reclamation methods (with and without topsoil application, Table I and Fig. 2). Research plots for different treatments were established on similar slope and aspect conditions to minimize the influence of physical setting on SOC accumulation rates. In total, 54 research plots, with six replications of each variant of 10 × 10 m, were randomly established across identified experimental patches on the spoil heap (Fig. 1). Additionally, six research plots were established adjacent to bare rock areas to assess the SOC content during spontaneous succession on bare overburden. A composite soil sample was collected from five subsamples (from four points at the corners and one in the middle of each plot) at two depths (0-10 cm and 10-20cm) in each plot. To calculate soil bulk density (BD), two independen samples from the center of each plot with intact soil structures were collected from each depth using 100 cm^3cylinders (Blake and Hartge, 1986).

The collected composite mineral soil samples were air-dried, sieved through a 2 mm mesh, and subjected to analyses for select physicochemical properties (Pansu *et al*., 2001). The soil texture was measured with a Fritsch GmbH Laser Particle Sizer (ANALYSETTE 22). The soil total organic carbon (SOCt), total nitrogen (Nt), and total sulfur (St) contents were analyzed with a LECO TruMac® CNS analyzer. The pH of the samples was measured in 1 M KCl solution (soil/liquid ratio 1:5, w/v) with a digital pH meter at 20 ° C, and the soil electrical conductivity (EC) (1:5 soil/solution ratio) was measured with a conductivity meter (Model: CD-201 NR 740, HYDROMET, Poland) at 20 °C with an accuracy of 1.0 µS cm^{-1}. The base exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were measured in 1 mol/L NH_4Ac by a Thermo Scientific™ iCAP™ 6000 Series ICP– OES instrument. To determine the bulk density (BD), the soil samples were dried at 105 ° C for 48 hours and then weighed. BD (g cm^{-3}) was calculated by dividing the mass of the oven-dried soil by the volume of its cylinder (Sumner, 2010).

The SOC content under succession on bare overburden without topsoil was assessed by computing the difference between the carbon content of the recent bare overburden without vegetation and the overall carbon content of the soil under succession on overburden without applied topsoil to reduce the effect of geogenic carbon from coal. This calculation was performed under the assumption that comparable overburden spoils were present on the surface at the initiation of pedogenesis during succession. Similar approaches have been employed by other researchers to address analogous issues (Reintam, 2004; Frouz *et al*., 2009).

SOM fractionation involved placing 20 g of soil, which was sieved through a 2 mm sieve, in a 200 ml test tube. Then, 90 ml of sodium polytungstate (SPT, 1.8 g cm^{-3}) was added, followed by shaking for 1 min and centrifugation for 30 min. The free light fraction (fLF) was then extracted using a pipette and collected on a glass fiber filter (Whatman GF/F, 0.7 µ m pore size, 47 mm diameter, Cytiva, USA). The remaining soil in the centrifuge tubes was mixed with another 90 ml of SPT and sonicated (60 W for 200 s) to disrupt aggregates, after which the occluded light fraction (oLF) was collected on a glass fiber filter. The fraction at the bottom of the tube was designated the mineral-associated fraction (MAF). After drying, the fractionated samples were weighed, and the carbon content of individual fractions (fLF, oLF, and MAF) was determined using a LECO TruMac® CNS analyzer (von Lü tzow *et al*., 2007).

Statistical analysis

Descriptive analysis was employed to evaluate the selected general soil properties of the study area. Prior to analysis, the datasets were tested for normality using the Kolmogorov–Smirnov test. Two-way analysis of variance (ANOVA) was used to investigate the effects of vegetation type and reclamation technology on the SOC fraction. The mean, standard deviation, and Tukey’s honestly significant difference (HSD) were calculated. Statistica 13.3 (StatSoft, Inc. 2014) software was used for statistical analyses. All means were considered different when $P < 0.05$. Correlations between the studied basic soil properties and C_{fLF}, C_{oLF}, and C_{MAF} were described using a Pearson’s correlation matrix. Furthermore, Principal Component Analysis (PCA) was performed using Canoco 5.1 software to differentiate multiple soil properties into independent significant
factors influencing soil reclamation and vegetation growth.

RESULTS

Basic soil properties

The soils on bare Carboniferous rock without topsoil under different vegetation types belong to the sandy loam texture class. In contrast, the topsoil-reclaimed layer has a loamy texture. Similarly, soils on bare rock were classified as very strongly acidic to strongly acidic unlike soils reclaimed with applied topsoil. WSTS resulted in greater BD than the other treatments. The highest St was observed for bare rock under all vegetation types. A higher content of Ca^{2+} was observed under successional and cultivation conditions with topsoil application across all vegetation types. The highest Mg^{2+} content was observed during succession on bare rock under all vegetation types (Table II).

TABLE II

Basic soil properties in the study site under each treatment (means ± SD)

Properties	Treatments								
	WSBR	WSTS	WCTS	GSBR	GSTS	GCTS	FSBR	FSTS	FCTS
Sand (%)	67 ± 5^{ab}	41 ± 3^{c}	51 ± 14^{bc}	56 ± 18^{abc}	56 ± 11^{abc}	43 ± 16^{bc}	69 ± 6^{a}	48 ± 10^{bc}	51 ± 18^{bc}
Silt (%)	26 ± 3^{bc}	48 ± 4^{a}	41 ± 13^{ab}	35 ± 16^{abc}	36 ± 8^{abc}	48 ± 15^{a}	24 ± 4^{c}	46 ± 11^{a}	42 ± 15^{a}
Clay (%)	7 ± 2^{b}	11 ± 2^{a}	8 ± 2^{b}	9 ± 2^{ab}	8 ± 3^{b}	9 ± 3^{ab}	7 ± 2^{b}	6 ± 0.7^{b}	7 ± 2^{b}
pH in KCl	4.6 ± 0.4^{b}	6.6 ± 0.9^{a}	7.3 ± 0.3^{a}	5.5 ± 1.2^{b}	7.0 ± 0.2^{a}	7.1 ± 0.5^{a}	5.5 ± 0.8^{b}	6.8 ± 0.4^{a}	7 ± 0.8^{a}
BD(g cm^{-3})	1.2 ± 0.1^{b}	1.6 ± 0.1^{a}	1.3 ± 0.2^{b}	1.2 ± 0.3^{b}	1.3 ± 0.17^{b}	1.3 ± 0.2^{b}	1.2 ± 0.2^{b}	1.3 ± 0.1^{b}	1.3 ± 0.2^{b}
Nt (%)	0.13 ± 0.06^{ab}	0.06 ± 0.03^{b}	0.16 ± 0.10^{a}	0.19 ± 0.03^{a}	0.15 ± 0.03^{ab}	0.15 ± 0.1^{ab}	0.19 ± 0.1^{a}	0.14 ± 0.1^{ab}	0.15 ± 0.1^{ab}

SOC (%)	2.4±1.5^{a}	1.3±0.8a	3.6±1.9^{a}	2.73±1.9^{a}	3.73±1.8^{a}	3.05±1.8^{a}	3.72±2.1^{a}	3.21±1.7^{a}	2.68±1.6^{a}
St (%)	0.29±0.07^{a}	0.02±0.0^{b}	0.03±0.01^{b}	0.33±0.07^{a}	0.07±0.06^{b}	0.08±0.1^{b}	0.39±0.2^{a}	0.04±0.02^{b}	0.04±0.03^{b}
C/N	18.0±3^{ab}	18.5±6^{ab}	24.0±10^{a}	14.0±9^{b}	23.0±6^{ab}	19.0±3^{ab}	13.0±10^{b}	22.0±1^{ab}	17.0±3^{ab}
Ca^{2+} [cmol(+) kg^{-1}]	0.42±0.1^{b}	1.47±0.6^{a}	1.49±0.4^{a}	0.51±0.2^{b}	1.34±0.2^{a}	1.28±0.2^{a}	0.49±0.1^{b}	1.38±0.6^{a}	1.23±0.7^{a}
K^{+} [cmol(+) kg^{-1}]	0.35±0.1^{ab}	0.24±0.1b	0.43±0.1^{ab}	0.37±0.1^{ab}	0.36±0.1^{ab}	0.48±0.1^{a}	0.37±0.1^{ab}	0.44±0.2^{ab}	0.46±0.2^{a}
Mg^{2+} [cmol(+) kg^{-1}]	4.15±0.5^{a}	1.87±0.4^{b}	3.09±0.9^{ab}	2.9±0.2^{b}	1.61±0.4^{b}	1.33±0.4^{b}	3.99±0.7^{a}	1.32±0.4^{b}	2.02±1.2^{b}
Na^{+} [cmol(+) kg^{-1}]	0.04±0.01^{a}	0.03±0.0^{a}	0.03±0.01^{a}	0.03±0.01^{a}	0.03±0.01^{a}	0.32±0.01^{a}	0.02±0.01^{a}	0.03±0.01^{a}	0.03±0.01^{a}

WSBR: woodland succession on bare rock; WSTS: woodland succession on topsoiling; WCTS: woodland cultivation on topsoiling; GSBR: grassland succession on bare rock; GSTS: grassland succession on topsoiling; GCTS: grassland cultivation on topsoiling; FSBR: forbland succession on bare rock; FSTS: forbland succession on topsoiling; FCTS: forbland cultivation on topsoiling. Means followed by different lowercase (a, b,c) are significantly different at $P < 0.05$.

Significantly higher SOCt levels were observed in the SBR and control (C-control) treatments compared to STS and CTS, primarily attributed to the higher geogenic carbon content derived from Carboniferous rock (Table III).

TABLE III

Total soil organic carbon contents (SOCt) under different reclamation treatment in 0-10 and 10-20 cm depth (means ± SD)

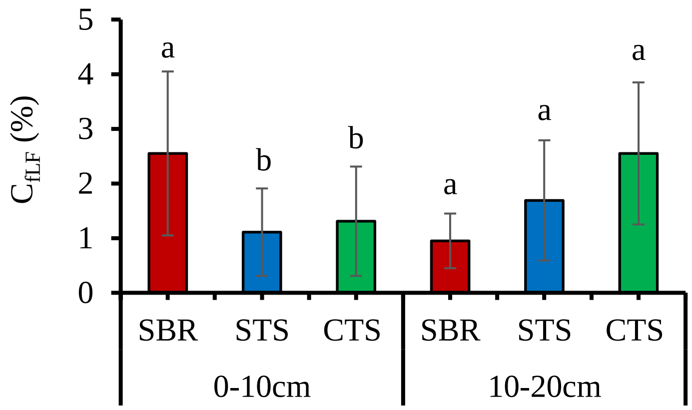
Parameter	Reclamation treatments	Depth (cm) 0-10	10-20
SOCt(%)	SBR	12.0±3.1^{a}	15.4±3.9^{a}
	STS	2.7±1.7^{b}	3.3±3.1^{b}
	CTS	3.1±1.7^{b}	4.5±3.9^{b}
	C – control	10.2±3.3^{a}	12.2±6.3^{a}

SBR: succession on bare rock; STS: succession on topsoiling; CTS: cultivation on topsoiling; C-control (collected from bare rock without vegetation). Means followed by different lowercase (a, b) are significantly different at $P < 0.05$.

The effect of reclamation and vegetation on SOC fractions

Reclamation had a significant effect on the free light fraction of carbon (C_{fLF}), occluded light fraction of carbon (C_{oLF}), and mineral-associated fraction of carbon (C_{MAF}). Vegetation type had a significant effect on the C_{oLF} at the 0-10 cm depth, and on the $C_{fLF,}$ C_{oLF} and C_{MAF} at the 10-20cm depth (Figs. 3 and 4).

Both cultivation and succession on reclaimed sites with topsoil treatment resulted in significantly higher C_{oLF} values, with 57% under STS and 58% under CTS at 0-10 cm depth, and 86% under STS and 85% under CTS at 10-20 cm depth, and higher C_{MAF} values, with 70% under STS and 74% under CTS at 0-10 cm depth, compared to succession on bare rock treatment. In contrast, succession on bare rock (SBR) had the highest C_{fLF} values of 56% and 48% at the 0-10 cm depth, and the highest C_{MAF} values of 72% and 62% at the 10-20 cm depth, compared to STS and CTS, respectively (Fig. 3).



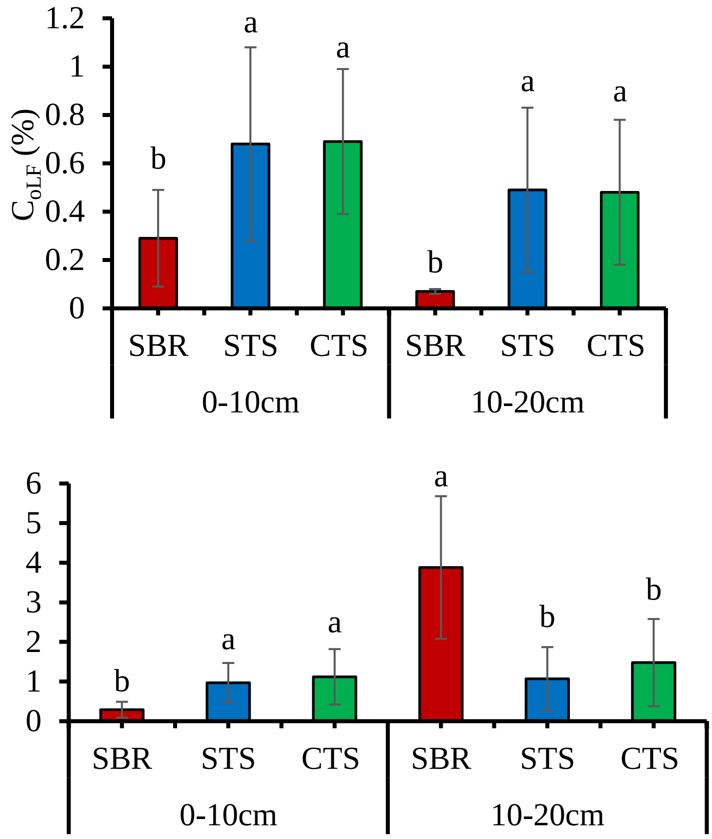
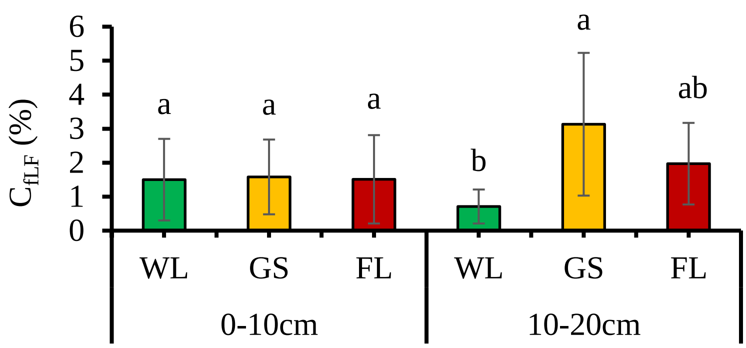


Fig. 3 The effect reclamation methods on C_{fLF}: free light fraction of carbon; C_{oLF}: occluded light fraction of carbon; and C_{MAF}: mineral-associated fraction of carbon. SBR: succession on bare rock; STS: succession on topsoiling; CTS: cultivation on topsoiling.

Restoration with different vegetation types resulted in significant differences in SOC fraction contents. The grassland (GL) treatment had significantly higher C_{oLF} (40.5%) at 0--10 cm depth and higher C_{fLF} (77%), C_{oLF} (56%), and C_{MAF} (46.5%) at 10--20 cm depth compared to the woodland (WL) treatment. In addition, C_{MAF} was significantly greater under GL (40%) at the 10-20 cm depth than under forbland (FL). Furthermore, FL had the highest C_{oLF} (53%) at the 10--20 cm depth compared to WL (Fig. 4).



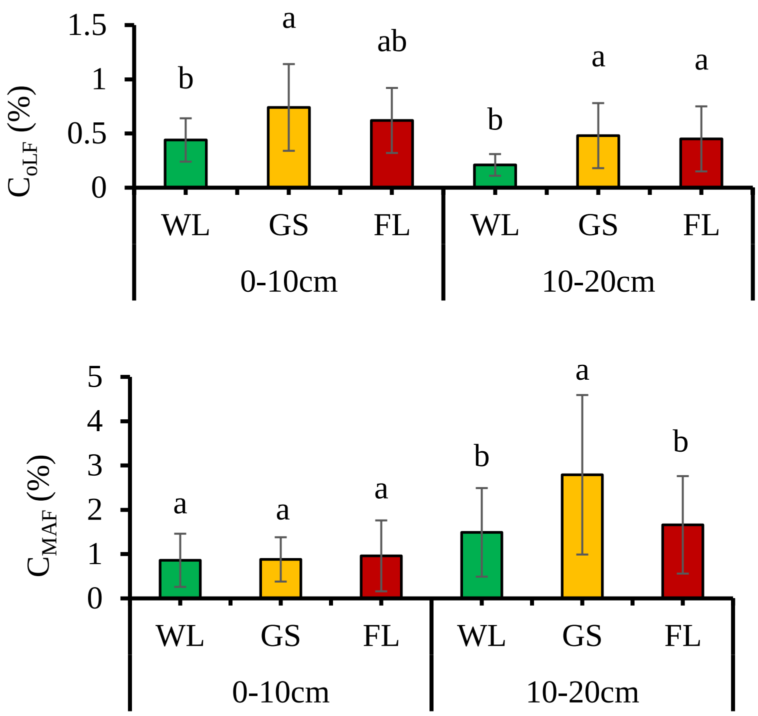


Fig. 4 The effect vegetation type on C_{fLF}: free light fraction of carbon; C_{oLF}: occluded light fraction of carbon; and C_{MAF}: mineral-associated fraction of carbon. WL: woodland; GS: grassland; FL: forbland.

The share of carbon fractions per soil organic carbon pool

Among the other SOC fractions, C_{flF} had the highest share per SOC pool, followed by C_{oLF}, at the 0-10 cm depth under all reclamation methods. However, at lower depths (10-20 cm), the soils under SBR contained more C_{MAF}. At the control site (bare overburden without any vegetation), a greater share of the C_{MAF} occurred at both depths (Fig. 5).

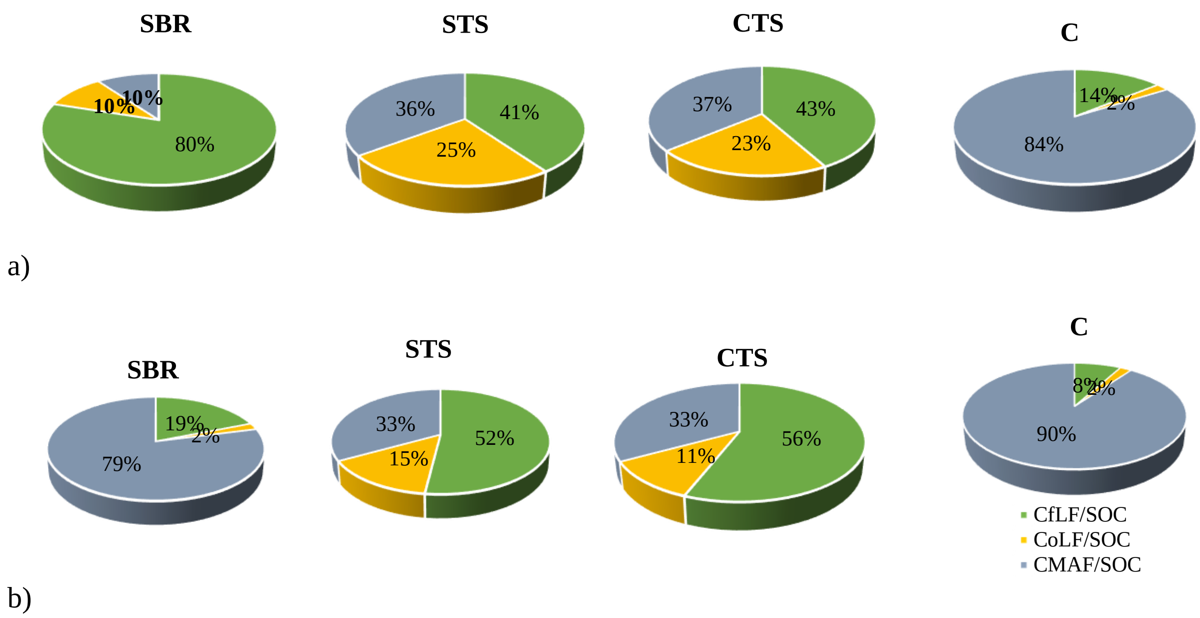


Fig. 5 Share of SOC fraction in the SOC pool in a) 0-10cm, and b) 10-20cm depths. SBR: succession on bare rock; STS: succession on applied topsoil; CTS: cultivation on applied topsoil, C: control.

The relationships between SOC and basic soil properties, and PCA

The C_{fLF} content was significantly positively correlated with sand, Nt, St, and Mg^{2+} and negatively correlated with clay content, BD, pH, and Ca^{2+}. The C_{oLF} content displayed a significant positive correlation with pH, Nt and K^+ but a negative correlation with BD and Mg^{2+}. The C_{MAF} content demonstrated significant positive correlations with pH, Nt, Ca^{2+}, and K^+ (Table IV).

TABLE IV

Relationships between soil organic carbon fractions and some basic soil parameters

Carbon fractions	Soil Properties									
	Sand	Silt	Clay	BD	pH_{KCL}	Nt	St	Ca^{2+}	K^+	Mg^{2+}	Na^+
C_{fLF}	0.43*	-0.23	-0.44*	-0.48*	-0.46*	0.45*	0.74*	-0.43*	0.09	0.38*	0.02
C_{oLF}	-0.15	-0.15	0.19	-0.32*	0.37*	0.47*	-0.12	0.29	0.32*	-0.33*	-0.04
C_{MAF}	-0.25	-0.01	0.28	-0.15	0.51*	0.41*	-0.25	0.50*	0.34*	0.01	-0.14

* - significant at $P < 0.05$

Principal Component Analysis (PCA) revealed two primary dimensions, PC1 and PC2, which collectively accounted for 86.7% of the total variance in the dataset (PC1: 63.8%; PC2: 22.9%), capturing the majority of variability in soil properties. PC1 differentiated soils based on carbon fraction relationships and development stages, with the positive side representing soils characterized by high C_{fLF}, sand, and silt, indicating less developed carbon stabilization. In contrast, the negative side featured soils with high C_{oLF} and C_{MAF}, along with higher clay content and pH, reflecting enhanced carbon sequestration, soil structure, and nutrient availability. PC1 was predominantly influenced by key soil variables such as Mg.Ex, St, sand, Ca.Ex, and clay, as indicated by their alignment along the horizontal axis.

PC2 distinguished soils by carbon stabilization and properties, with the positive side indicating lower carbon stabilization associated with higher silt and bulk density, while the negative side highlighted higher carbon stabilization driven by higher SOC, Nt, C_{oLF}, and C_{MAF}, promoting improved soil fertility and carbon sequestration. PC2 was primarily associated with SOC, K.Ex, and silt content. Additionally, soils under all vegetation types on SBR plots exhibited distinct properties compared to those on STS and CTS plots (Fig. 6).

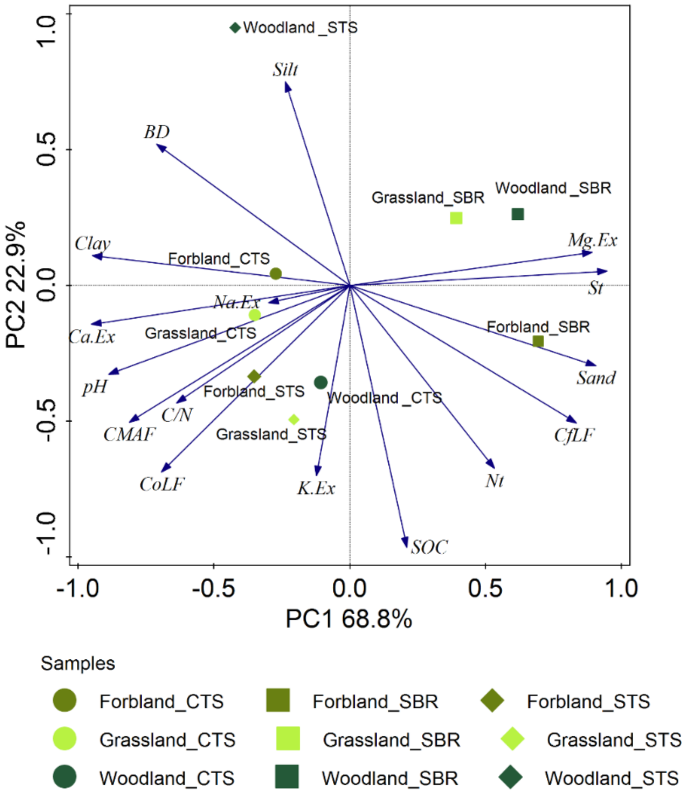


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Fig. 6 Principal component analysis (PCA) biplot of soil properties under different vegetation and reclamation methods.

DISCUSSION

The different reclamation methods resulted in significant variations in the content of soil SOC fractions at the post-mining site. In this study, a higher content of the free light fraction (C_{fLF}) was observed in the soil under SBR at a depth of 0--10 cm. This observation may be attributed to the production of fine roots (Świątek *et al*., 2019). In nutrient-poor soils, plants often increase the production of fine roots to sustain growth and optimize resource uptake (Li *et al*., 2022). Additionally, this difference can be linked to the limited colonization of microorganisms responsible for organic matter decomposition, which is influenced by the unfavorable conditions of the post-mining site (Frouz *et al*., 2008). A study conducted at the same site by Józefowska *et al*. (2023) revealed that reclamation was a major driver of soil fauna activity, with a higher abundance of soil fauna observed in topsoil-reclaimed areas compared to areas undergoing succession on bare rock overburden. Soil macro- and microorganisms play a crucial role in litter decomposition and soil organic matter (SOM) stabilization through their feeding activities, protection of microbial biomass, excretion of metabolites, and accumulation of dead cells in the soil (Six *et al*., 2006; Gougoulias *et al*., 2014; Frouz, 2018).

The occluded light fraction (C_{oLF}) was significantly greater in soils under reclamation with topsoiling compared to those under succession on bare rock at both the 0--10 cm and 10--20 cm depths. This difference may be attributed to the enhanced rate of humification in topsoil-reclaimed sites (Zhao *et al*., 2015) and improvements in soil texture (Min *et al*., 2022). The humified carbon fraction represents a stable SOC pool that contributes to long-term carbon sequestration in soils (Eusterhues *et al*., 2003; Kalisz & Lachacz, 2023). Similarly, Das and Maiti (2016) demonstrated that reclaimed sites contained higher amounts of stable organic carbon than unreclaimed sites at both depths (0--10 cm and 10--20 cm). Organic carbon stability is influenced more by complex interactions among microbial communities, enzymatic activities, substrates, and environmental conditions than by the chemical recalcitrance of carbon substrates (Schmidt *et al*., 2011; Dungait *et al*., 2012).

The amount of mineral-associated fraction (C_{MAF}) varied significantly with reclamation technique and depth. In the surface layer (0--10 cm), the topsoil at the reclaimed site had significantly greater C_{MAF} than that at the successional site on bare rock. Conversely, at lower depths (10–20 cm), the site with succession on bare rock exhibited significantly greater C_{MAF} than that at the reclaimed site. This difference may result from the weathering and leaching of geogenic carbon from the uppermost soil horizons (Nash, 2012; Schindlbacher *et al*., 2019) and the higher geogenic organic carbon content in the subsoils of the SBR site (Rumpel *et al*., 2003). Consistent with these findings, Das and Maiti (2016) reported significantly greater amounts of mineral-associated carbon fractions at unreclaimed sites. Additionally, a study conducted in Ohio, USA, demonstrated that coal carbon contributes up to 92% of the SOC at reclaimed mining sites (Ussiri & Lal, 2008). Consequently, even a small amount of coal particles can complicate the accurate measurement of SOC. Ussiri and Lal (2005) highlighted the difficulty of detecting small increments in recently deposited or plant-derived SOC against a large carbon background from coal particles.

In the top layer (0--10 cm), all reclamation treatments (SBR, STS, and CTS) resulted in a greater proportion of the C_{fLF} within the SOC pool, followed by C_{oLF}. In contrast, in the sublayer (10--20 cm), SBR demonstrated a greater proportion of CMAF, while STS and CTS showed a greater proportion of C_{fLF}. This suggests that topsoiling introduces native C_{fLF} and enhances fresh SOC accumulation by improving the physical and chemical properties of the soil substrate, thereby facilitating vegetation establishment (Pietrzykowski and Krzaklewski, 2007). Čížková *et al*. (2018) revealed that reclamation of mining sites with topsoil application resulted in greater SOC accumulation compared to unreclaimed sites. Additionally, the higher proportion of C_{MAF} in the control plot compared to the SBR, STS, and CTS plots underscores the role of vegetation in enhancing recent SOM levels, resulting in a greater proportion of the labile fraction in reclaimed post-mining sites (Yuan *et al*., 2018).

Restoration with different vegetation types resulted in significant differences in SOC fraction contents, with grassland vegetation playing a more significant role than other types. The grassland treatment showed significantly higher CoLF at the 0--10 cm depth and higher CfLF, CoLF, and CMAF at the 10--20 cm depth compared to the woodland. Additionally, grassland exhibited higher CMAF at the 10--20 cm depth compared to the forbland. This is likely due to the increased formation of microaggregates under grassland, which provide greater protection to SOC. Forbland also had significantly greater CoLF at the 10--20 cm depth than woodland. Nickels and Prescott (2021) reported that grassland sites had significantly more physically protected SOC than deciduous tree sites, consistent with the findings of Guidi *et al*. (2014), who attributed the higher SOC in grasslands to its storage in small aggregates. SOC accumulation in grassland soils is linked to greater amounts of fine roots and root exudates compared to woodlands, enhancing the association between root biomass and mineral surfaces (Wei *et al*., 2012). The dynamics of stable soil carbon are influenced by the composition and quantity of root exudates, which affect the turnover and accumulation of mineral-associated organic matter. Specifically, carbon components in root exudates can interact with microbial metabolites, dead detritus, or soil minerals and persist in the soil due to physical protection provided by aggregates or mineral–chemical interactions (Dijkstra *et al*., 2021; Panchal *et al*., 2022). However, fine root variation among vegetation types is not a strong driver of SOC stabilization in the top layer (0–10 cm). This could be associated with the fact that SOC derived from soil inputs contributes to SOC buildup.

In grasslands, belowground biomass, characterized by an extensive fibrous root system, plays a significant role in influencing SOC levels (Gilmullina *et al*., 2023). Another factor contributing to greater SOC stocks in small aggregates in grasslands may be the dominance of arbuscular mycorrhizae (AM). AM-associated grasses release glomalin proteins, which act as binding agents, increasing aggregate stability and promoting larger pools of physically and chemically stable SOC (Dignac *et al*., 2017). Various studies have shown that arbuscular mycorrhizal fungi are more abundant in grasslands and herbaceous areas than in forests (O'Connor *et al*., 2002; Treseder & Cross, 2006; Sepp *et al*., 2018). Wick and Daniels (2009) also observed that early succession communities, characterized by the prevalence of grasses and forbs, exhibited greater rates of particulate organic matter accumulation and aggregate formation compared to late-succession forested counterparts. Therefore, grasslands play a crucial role in stabilizing soil organic carbon at the studied reclaimed post-mining site.

SOC fractions were closely associated with and correlated to soil physicochemical properties. Our results showed that C_{fLF} was positively correlated with sand, Nt, St, and Mg^{2+}; C_{oLF} was correlated with pH, Nt, and K^{+}; and C_{MAF} was correlated with pH, Nt, Ca^{2+}, and K^{+}. Research has suggested that soil texture, particularly the distribution of sand, silt, and clay, can influence the distribution of SOC fractions. Sandy soils often exhibit a greater proportion of labile SOC fractions compared to soils with other textures due to their lower mineral protection and faster microbial turnover (Lützow *et al*., 2006; Kleber *et al*., 2007; Yuan *et al*., 2018). St can be incorporated into soil organic matter and inorganic carbon, leading to the formation of sulfur-containing organic compounds that stabilize SOC fractions, including the labile fraction (Franzluebbers, 2023). Ca^{2+} contributes to SOC persistence by mediating physicochemical interactions between organic compounds, including sorption, coprecipitation, complexation, and occlusion within aggregates, which promote the persistence of mineral-associated organic matter (Shabtai *et al*., 2023).

As demonstrated by the correlation analysis and PCA, C_{fLF} exhibits a positive correlation with Mg^{2+}, suggesting that the presence of Mg^{2+} may contribute to a higher proportion of labile SOC fractions (Franzluebbers, 2023). A slight increase in soil pH has been found to enhance SOC storage, leading to greater plant diversity and improved SOC stabilization (Zhou *et al*., 2019). Thus, in addition to reclamation methods and vegetation types, soil physicochemical properties significantly influence the stabilization of SOC fractions in post-mining sites. Overall, soils under different reclamation and vegetation types exhibited distinct properties, with higher C_{fLF} indicating less developed carbon stabilization and higher C_{oLF} and C_{MAF} indicating greater stability and enhanced soil quality.

CONCLUSIONS

This research highlights the combined influence of reclamation methods and vegetation functional groups on SOC fractions in a Carboniferous spoil heap following hard coal mining. Notably, under SBR at a depth of 0–10 cm, a greater C_{fLF} was observed, likely due to adverse conditions hindering microbial colonization and organic matter decomposition. Reclaimed sites with topsoil exhibited a significant increase in C_{oLF}, indicating that enhanced humification and improved soil texture are critical for maintaining stable SOC pools responsible for long-term carbon sequestration. Furthermore, C_{MAF} varied with reclamation technique and depth, with topsoil-reclaimed sites displaying higher C_{MAF} in the surface layer but lower C_{MAF} in the sublayer compared to sites undergoing succession on bare rock. Reclamation method emerged as the predominant factor influencing SOC fractions, particularly in the upper layer, overshadowing the impact of vegetation type. Grassland vegetation played a significant role in stabilizing soil organic carbon at the studied post-mining site. These results underscore the importance of topsoil reclamation and grassland vegetation in shaping the dynamics of SOC fractions in post-mining environments.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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