SUPPLEMENTARY MATERIAL

Soil carbon sequestration and land use: A spatial analysis from Kłodzko County, SW Poland

Aleksandra Wiśniewska*[1], Beata Łabaz[2], Grzegorz Chrobak[3], Aleksandra Gierko[4], Katarzyna Tokarczyk-Dorociak[1]

[1] Wrocław University of Environmental and Life Sciences, Department of Landscape Architecture, Norwida St, 25, 50-375 Wrocław, Poland

[2] Wrocław University of Environmental and Life Sciences, Institute of Soil Science, Plant Nutrition and Environmental Protection, Norwida St, 25, 50-375 Wrocław, Poland

[3] Wrocław University of Environmental and Life Sciences, Department of Systems Research, Norwida St, 25, 50-375 Wrocław, Poland

[4] Wrocław University of Science and Technology, Faculty of Architecture, Department of Public Architecture, Basics of Design and Environmental Development, Bolesława Prusa St, 53/55, 50-317 Wrocław

* Corresponding author

Table S1. Analysis of soils of Kłodzko County for potential for carbon sequestration[1)]

Type of soils according to			Soil appraisal
Soil-agricultural map at a 1:5,000 (WODGIK, 2024)	**Kabała *et al.* (2019)**	**IUSS Working Group WRB (2022)**	
Gleby torfowe i murszowo-torfowe [Peat and peat-muck soils]	Soil type: Gleby torfowe [Peat soils] Gleby murszowe [Murshic soils]	Histosols	The most valuable soils that are important for carbon sequestration.
Gleby mułowo-torfowe i torfowo-mułowe [Silt-peat and peat-silt soils]	Soil type: Gleby limnowe [Limnic soils] Soil subtype: gleby mułowe [limnic muddy soils]		
Czarnoziemy i czarne ziemie właściwe [Chernozemic soils (Chernozems and black earths)]	Soil type: Czarnoziemy [Chernozems] Czarne ziemie [Black earths]	Chernozems and Phaeozems	Particularly valuable soils that are important for carbon sequestration.
Gleby murszowo-mineralne i murszowate [Mineral and mucky soils]	Soil type: Gleby murszowate [Semimurshic soils]	Umbrisols	
Gleby brunatne właściwe [Brown soils proper]	Soil type: Gleby brunatne [Brown soils] Soil subtype: gleby brunatne właściwe [ordinary brown soils]	Cambisols	
Rędziny brunatne [Brown rendzinas]	Soil type: Rędziny brunatne [Brown rendzinas]	Leptosols	
Mady brunatne [Brown fluvisols]	Soil type: Mady brunatne [Brown alluvials]	Fluvisols	
Mady [Fluvisol]	Soil type: Mady właściwe [Ordinary alluvial soils]		
Gleby bielicowe i pseudobielicowe [Podzolic and pseudo-podzolic soils]	Soil type: Gleby bielicowe [Podzolic soils] Gleby płowe [Clay-illuvial soils] Soil subtype: płowe zbielicowane [podzoilic clay-illuvial soils]		Valuable soils that are important for carbon sequestration.
Gleby brunatne wyługowane i brunatne kwaśne [Leached brown soils and acid brown soils]	Soil type: Gleby brunatne [Brown soils] Soil subtype: brunatne wyługowane [leached brown soils] brunatne kwaśne [acid brown soils]	Cambisols	
Rędziny o słabo wykształconym profilu [Poorly formed rendzina profile]	Soil type: Gleby inicjalne [Raw mineral soils] Soil subtype: litosole [lithosols] rędziny inicjalne skaliste [raw rocky rendzinas]	Litosols/Arenosols /Regosols	

continue Tab. 1

Type of soils according to			Soil appraisal
Soil-agricultural map at a 1:5,000 (WODGIK, 2024)	**Kabała *et al*. (2019)**	**IUSS Working Group WRB (2022)**	
Gleby aluwialne glejowe [Gleyic alluvial soils]	Soil type: Mady właściwe [Ordinary alluvial soils] Soil subtype: mady gruntowo-glejowe [gleyic oridnary alluvial soils] mady opadowo-glejowe [stagnogleyic oridnary alluvial soils]	Fluvisols	
Gleby glejowe [Gleyic soils]	Soil type: Gleby gruntowo-glejowe [Gleysols] Gleby opadowo-glejowe [Stagnosols]	Gleysols	
Czarnoziemy i czarne ziemie zdegradowane i gleby szare [Degraded chernozem and black soils and grey soils]	Soil type: Czarnoziemy [Chernozems] Czarne ziemie [Black earths] Gleby szare [Grey soils]	Umbrisols and Phaeozems	Heavily degraded soils in need of reclamation, but important for carbon sequestration.

[1)] Original Polish soil type names are used to ensure terminological precision and clarity of interpretation.

Source: own study.

Table S2. Assessing the use of carbon sequestration potential

Land use[1)]	Type of soil	Value[2)]	Explanation
Urban fabric Industrial, commercial and transport areas Mines, extraction sites, and construction areas	all types of soils	−2	Urbanisation, including hardening and replacing topsoil, severely degrades land, affecting soil structure and reducing organic carbon (Herrmann, Schifman and Shuster, 2020). Transforming land for urban use involves grading and excavation, which reshapes the landscape (Jones *et al*., 2014). Mining disrupts soil by removing humus, accumulating heavy metals and depleting nutrients, harming plant and microorganism growth. It also promotes erosion and contaminant migration (Wong, 2003; Ungaro *et al*., 2022).
Urban green and recreational spaces	all types of soils	0	Urban green and recreational areas can both benefit and harm soils, depending on factors like urbanisation level, land-use practices, and vegetation. In highly urbanised areas, green spaces can improve soil structure and water infiltration, especially with sustainable management and native or drought-resistant plants. However, activities like trampling, pollution, and the use of non-native species can degrade soil, compact it, and reduce biodiversity. Poorly planned areas, particularly in dense environments, can lead to erosion, waste contamination, and loss of fertile topsoil. The impact of these areas varies based on their design, maintenance, and use, making the overall effect neutral (Kumar and Hundal, 2016; Lindén *et al*., 2020; O'Riordan *et al*., 2021; Todorova and Zhiyanski, 2023).
Arable land	the most valuable soils that are important for carbon sequestration	−2	Peatland drainage for cultivation leads to intensification of greenhouse gas emissions, especially carbon dioxide, which is released due to aerobic decomposition of peat (Jarosz and Faber, 2024). This process significantly contributes to the concentration of CO_2 in the atmosphere and accelerates climate change.
	particularly valuable soils that are important for carbon sequestration	−1	Soils rich in organic matter are among the most agriculturally valuable (Pikuła, 2015). With appropriate practices, agriculture can have minimal negative impact on such soils (Foereid and Høgh-Jensen, 2004). However, long-term cereals monocultures has been found to degrade humus quality. Intensive land use is a major factor threatening the quality and persistence of soils, as it accelerates soil depletion processes (Witkowska-Walczak, Walczak and Sławiński, 1999). Continuous cultivation, particularly when involving regular ploughing and mineral fertilisation, reduces humus content in the topsoil and gradually transforms soils into "grey soils" (Kowalinski *et al*., 1987; Chodorowski *et al*., 2019).

continue Tab. 2

Land use[1)]	**Type of soil**	**Value**[2)]	**Explanation**
Arable land	valuable soils that are important for carbon sequestration	−1	Agricultural cultivation disrupts soil structure and leads to a reduction in organic matter content in all soil types (Kabała *et al*., 2019; IUSS Working Group WRB, 2022). However, due to their lower initial organic matter content, these soils have lower carbon sequestration potential, so agricultural use does not lead to a significant loss of this function compared to soils with higher organic carbon content (Gerzabek *et al*., 2006; Kodesova *et al*., 2011; Jonczak, 2012; Kurganova *et al*., 2022).
	heavily degraded soils in need of reclamation, but important for carbon sequestration	0	Agriculture can have both positive and negative effects on degraded soils, depending on management practices. Sustainable techniques such as no-till farming, crop rotation, and organic farming help restore soil health, improve carbon sequestration, and reduce erosion. However, conventional practices such as intensive tillage, monoculture cropping, and heavy use of synthetic fertilisers can exacerbate soil degradation, promote carbon loss, and disrupt soil ecosystems. Thus, the impact of agriculture on soil carbon dynamics is highly context-dependent, with the land-soil carbon balance index considered neutral (Mikha *et al*., 2014; Lal, 2015; Mayel, Jarrah and Kuka, 2021).
Pastures and meadows	all types of soils	2	Meadows and pastures stabilise soil, reduce erosion, and increase organic matter, boosting carbon sequestration. Permanent vegetation with minimal intervention improves soil properties, supporting long-term carbon storage (Celik, 2005; Gerzabek *et al*., 2006; Kodesova *et al*., 2011; Mayel *et al*., 2021). Restoring vegetation cover, such as with cover crops and trees, is the most effective way to rehabilitate degraded soils and promote carbon sequestration (Lal, 2003; Lal, 2015; Zhang *et al*., 2019).
Heterogeneous agricultural areas	all types of soils	0	Due to the heterogeneous nature of this land use, which encompasses a mix of various agricultural practices with both beneficial and detrimental impacts, its overall environmental effect is generally assessed as neutral Kosztra *et al*. (2019).
Forests Shrub and woodland vegetation	all types of soils	2	The presence of forests on soils with high organic matter content significantly increases the potential for long-term carbon sequestration by enhancing soil stability, promoting humus formation, and facilitating the accumulation of organic carbon. In such conditions, the capacity of the ecosystem to capture and store atmospheric carbon is considerably strengthened, contributing to climate change mitigation and improving soil quality. As a result, the utilization potential index is assessed as very high, reflecting the strong capacity of these forested areas to act as effective carbon sinks (Lasota *et al*., 2019).

continue Tab. 2

Land use[1)]	**Type of soil**	**Value**[2)]	**Explanation**
Forests Shrub and woodland vegetation	all types of soils	2	Forests established on soils with lower organic matter content have reduced carbon sequestration potential compared to those on organic-rich soils. Nevertheless, forests on these soils contribute to carbon sequestration by increasing organic matter inputs, enhancing microbial activity, and improving soil structure, thereby supporting long-term carbon stabilisation (Carter *et al*., 1992; Bens *et al*., 2007; Jonczak, 2012; Wiesmeier *et al*., 2013; Liebmann *et al*., 2022). Afforestation of degraded soils is one of the most effective strategies for their restoration, as it enhances soil structure, increases organic matter content, and promotes the accumulation of stable carbon pools. Tree root systems facilitate soil aeration and microbial activity, accelerating nutrient cycling and organic matter formation. Additionally, afforestation contributes to long-term carbon sequestration by stabilising organic carbon in soil aggregates and reducing erosion, thereby improving the resilience of degraded ecosystems.

[1)] All land-use types listed in Figure 4 were assessed, except for “Inland wetlands”, as no soil type data is available for these areas.

[2)] Value explanation: 2 = full (completely preserved) potential of soils for sequestration, 1 = partially preserved potential of soils in CO_2 sequestration, 0 = impossible to determine precisely, dependent on detailed use, −1 = partially lost potential of soils in CO sequestration, −2 = completely lost potential of soils in CO sequestration.

Source: own study.

REFERENCES

Bens, O. *et al*. (2007) "Water infiltration and hydraulic conductivity in sandy Cambisols: Impacts of forest transformation on soil hydrological properties," *European Journal of Forest Research*, 126(1), pp. 101–109. Available at: https://doi.org/10.1007/s10342-006-0133-7.

Carter, M.R. *et al*. (1992) "Organic carbon and nitrogen stocks and storage profiles in cool, humid soils of eastern Canada," *Canadian Journal of Soil Science*, 77(2), pp. 205–210. Available at: https://doi.org/10.4141/S96-111.

Celik, I. (2005) "Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey," *Soil and Tillage Research*, 83(2), pp. 270–277. Available at: https://doi.org/10.1016/j.still.2004.08.001.

Chodorowski, J. *et al*. (2019) "Czarnoziemy Lubelszczyzny [Chernozems of Lubelszczyzna (eastern Poland)]," *Soil Science Annual*, 70(3), pp. 258–269. Available at: https://doi.org/10.2478/ssa-2019-0023.

Foereid, B. and Høgh-Jensen, H. (2004) "Carbon sequestration potential of organic agriculture in northern Europe – A modelling approach," *Nutrient Cycling in Agroecosystems*, 68(1), pp. 13–24. Available at: https://doi.org/10.1023/B:FRES.0000012231.89516.80.

Gerzabek, M.H. *et al*. (2006) "How are soil use and management reflected by soil organic matter characteristics: A spectroscopic approach," *European Journal of Soil Science*, 57(4), pp. 485–494. Available at: https://doi.org/10.1111/j.1365-2389.2006.00794.x.

Herrmann, D.L., Schifman, L.A. and Shuster, W.D. (2020) "Urbanization drives convergence in soil profile texture and carbon content," *Environmental Research Letters*, 15(11), 114001. Available at: https://doi.org/10.1088/1748-9326/abbb00.

IUSS Working Group WRB (2022) *World reference base for soil resources: International soil classification system for naming soils and creating legends for soil maps*. 4th edn. Vienna, Austria: International Union of Soil Sciences (IUSS). Available at: https://www.isric.org/sites/default/files/WRB_fourth_edition_2022-12-18.pdf (Accessed: March 10, 2025).

Jarosz, Z. and Faber, A. (2024) "Praktyki rolnictwa węglowego. Praca przeglądowa [Coal farming practices. A review paper]," *Agronomy Science*, 79(3), pp. 31–43. Available at: https://doi.org/10.24326/as.2024.5347.

Jonczak, J. (2012) "Effect of land use on the carbon and nitrogen forms in humic horizons of Stagnic Luvisols," *Journal of Elementology*, 19(4), pp. 1037–1048. Available at: https://doi.org/10.5601/jelem.2014.19.3.345.

Jones, D.K. *et al*. (2014) "Tracking geomorphic signatures of watershed suburbanization with multitemporal LiDAR," *Geomorphology*, 219, pp. 42–52. Available at: https://doi.org/10.1016/j.geomorph.2014.04.038.

Kabała, C. *et al*. (2019) *Systematyka gleb Polski [Polish soil taxonomy]*. 6th edn. Wrocław–Warszawa: Polskie Towarzystwo Gleboznawcze, Komisja Genezy Klasyfikacji i Kartografii Gleb. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Polskie Towarzystwo Gleboznawcze.

Kodesova, R. *et al*. (2011) "Soil structure and soil hydraulic properties of Haplic Luvisol used as arable land and grassland," *Soil and Tillage Research*, 111(2), pp. 154–161. Available at: https://doi.org/10.1016/j.still.2010.09.007.

Kosztra, B. *et al*. (2019) *Updated CLC illustrated nomenclature guidelines*. Wien: Environment Agency Austria. Available at: https://land.copernicus.eu/content/corine-land-cover-nomenclature-guidelines/docs/pdf/CLC2018_Nomenclature_illustrated_guide_20190510.pdf (Accessed: March 18, 2025).

Kowalinski, S. *et al*. (1987) "Micromorphological interpretation of physical and chemical processes in black earth soils of different regions of Poland," *Soil Science Annual*, 38(2), pp. 77–100.

Kumar, K. and Hundal, L.S. (2016) "Soil in the city: Sustainably improving urban soils," *Journal of Environmental Quality*, 45(1), 2. Available at: https://doi.org/10.2134/jeq2015.11.0589.

Kurganova, I.N. *et al*. (2022) "Changes in the carbon stocks, microbial and enzyme activities of Retic Albic Podzol in southern taiga during postagrogenic evolution," *Eurasian Soil Science*, 55(7), 895–910. Available at: https://doi.org/10.1134/S1064229322070079.

Lal, R. (2003) "Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry," *Land Degradation and Development*, 14(3), pp. 309–322. Available at: https://doi.org/10.1002/ldr.562.

Lal, R. (2015) "Restoring soil quality to mitigate soil degradation," *Sustainability*, 7(5), pp. 5875–5895. Available at: https://doi.org/10.3390/su7055875.

Lasota, J. *et al*. (2019) "Forest habitats and forest types on chernozems in south-eastern Poland," *Soil Science Annual*, 70(3), pp. 234–243. Available at: https://doi.org/10.2478/ssa-2019-0021.

Liebmann, P. *et al*. (2022) "Biogeochemical limitations of carbon stabilization in forest subsoils," *Journal of Plant Nutrition and Soil Science*, 185(1), pp. 35–43. Available at: https://doi.org/10.1002/jpln.202100295.

Lindén, L. *et al*. (2020) "Quantifying carbon stocks in urban parks under cold climate conditions," *Urban Forestry and Urban Greening*, 49, 126633. Available at: https://doi.org/10.1016/j.ufug.2020.126633.

Mayel, S., Jarrah, M. and Kuka, K. (2021) “How does grassland management affect physical and biochemical properties of temperate grassland soils? A review study,” *Grass and Forage Science*, 76(2), pp. 215–244. Available at: https://doi.org/10.1111/gfs.12512.

Mikha, M.M. *et al*. (2014) “Remediation/restoration of degraded soil: II. impact on crop production and nitrogen dynamics,” *Agronomy Journal*, 106(1), pp. 261–272. Available at: https://doi.org/10.2134/agronj2013.0279.

O’Riordan, R. *et al*. (2021) “The effects of sealing on urban soil carbon and nutrients,” *SOIL*, 7(2), pp. 661–675. Available at: https://doi.org/10.5194/soil-7-661-2021.

Pikuła, D. (2015) “Aspekty środowiskowe gospodarowania materią organiczną w rolnictwie [Environmental aspects of managing the organic matter in agriculture],” *Economic and Regional Studies*, 8(2), pp. 98–112. Available at: https://www.ers.edu.pl/ASPEKTY-SRODOWISKOWE-GOSPODAROWANIA-MATERIA-ORGANICZNA-W-ROLNICTWIE,93075,0,1.html (Accessed: January 5, 2025).

Todorova, E.R. and Zhiyanski, M.K. (2023) “Study on soil quality in different functional zones of Sofia region,” *One Ecosystem*, 8, e101381. Available at: https://doi.org/10.3897/oneeco.8.e101381.

Wiesmeier, M. *et al*. (2013) “Storage and drivers of organic carbon in forest soils of southeast Germany (Bavaria) – Implications for carbon sequestration,” *Forest Ecology and Management*, 295, pp. 162–172. Available at: https://doi.org/10.1016/j.foreco.2013.01.025.

Witkowska-Walczak, B., Walczak, R. and Sławiński, C. (1999) “Soil water potential-moisture characteristics of Polish chernozems,” *Acta Agrophysica*, 22, pp. 265–273.

WODGIK (2024) "Mapa glebowo-rolnicza, skala 1:5.000 [Soil-agricultural map of Kłodzko County, scale 1:5,000],” *Katalog zasobów [Shapefile dataset]*. Licencja nr MGW-I.7522.67.2024_02_N, 2024. Wrocław: Urząd Marszałkowski Województwa Dolnośląskiego. Wojewódzki Ośrodek Dokumentacji Geodezyjnej i Kartograficznej. https://geoportal.dolnyslask.pl/cat/mapa?page=3&sort=name&dir=up (Accessed: March 12, 20250.

Wong, M.H. (2003) “Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils,” *Chemosphere*, 50(6), pp. 775–780. Available at: https://doi.org/10.1016/S0045-6535(02)00232-1.

Zhang *et al*., (2019) “Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China,” *Science of the Total Environment*, 650(2), pp. 2657–2665. Available at: https://doi.org/10.1016/j.scitotenv.2018.09.372.