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

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**Abstract:** The complex interplay between soil characteristics and land management practices plays a crucial role in shaping terrestrial carbon sequestration potential, a process widely recognised as a key component of climate change mitigation strategies. In regions characterised by high pedodiversity, such as those found in Central Europe, integrated analyses combining detailed soil survey data with land cover classifications reveal pronounced spatial mismatches between the inherent soil carbon storage capacity and prevailing land use patterns. While forest and grassland ecosystems generally optimise carbon retention on organic-rich soils, the continuing expansion of agriculture, infrastructure, and urban areas often leads to the degradation and fragmentation of these natural carbon sinks. Such land use changes frequently reduce soil organic carbon stocks, weaken ecosystem resilience, and limit the capacity to buffer climate extremes. Despite their fundamental role in regulating biogeochemical cycles, the ecological value of soils as carbon reservoirs remains underrepresented in spatial planning frameworks, which still tend to prioritise short-term productivity over long-term ecosystem functionality. This oversight contributes to the vulnerability of carbon-dense soils to irreversible losses and undermines broader climate adaptation efforts. Shifting towards a land-use planning paradigm that systematically incorporates ecosystem service valuation – particularly carbon storage potential – would mark a transformative step in environmental governance. Using Kłodzko County as a case study, this research develops a transferable methodological framework that links soil typology with land management regimes, offering decision-makers practical, spatially explicit tools to strengthen climate resilience through more sustainable and ecologically informed development strategies.

**Keywords:** carbon sinks, ecosystem, land use, soil potential, soil carbon sequestration

## INTRODUCTION

Soils are crucial for environmental stability and climate regulation, with the Sixth IPCC Report highlighting the increased drought risk in Western and Central Europe due to human-driven climate change. Although the UN's Sustainable Development Goals emphasise soil conservation, poor land management in Europe exacerbates soil degradation (EEA, 2019; IPCC, 2023).

Soil biodiversity supports ecosystem functions while also representing significant climate mitigation potential through carbon sequestration (Lal, Negassa and Lorenz, 2015; Siebielec *et al.*, 2020). Soil organic matter (SOM) plays a fundamental role in carbon storage and contributes to the reduction of greenhouse gas emissions. However, inadequate soil management practices can accelerate the mineralisation of SOM, leading to increased $CO_2$ emissions (Sapek, 2009; Baveye *et al.*, 2020). Through photosynthesis, plants transfer atmospheric $CO_2$ to the soil, facilitating long-term carbon storage, with optimised practices like cover cropping and reduced tillage enhancing sequestration (Schmidt *et al.*, 2011; Amelung *et al.*, 2020). As the largest terrestrial carbon reservoir, soil stores more carbon than the atmosphere and vegetation combined (Paustian *et al.*, 2016; IPCC, 2023).

Soil classification reflects pedogenic processes that influence carbon sequestration potential (FAO, 2017; Kabała *et al.*, 2019). The European Union prioritises soil conservation through initiatives such as Horizon Europe's "A soil deal for Europe" (EC, no date) and the Common Agricultural Policy. At the global level, initiatives such as SoilGrids (Fig. 1) and the FAO's Global Soil Organic Carbon Sequestration Potential Map provide data to support climate strategies (FAO GloSIS, no date).

Despite growing research efforts, soil conservation policies remain insufficient. Institutions such as The Institute of Soil Science and Plant Cultivation are advancing studies on soil carbon sequestration (Jadczyszyn and Smreczak, 2017; Turbiak, Ćwiklińska and Duda, 2017; Pietrzak and Hołaj-Krzak, 2022), yet the integration of conservation measures into policy remains essential for effective climate change mitigation.

The main objective of the study is to assess how different types of land use limit or enhance the contribution of soils to $CO_2$ sequestration. The specific goal is to assess whether the current land use in Kłodzko County enables the full utilisation of soil potential for climate change adaptation, particularly through carbon sequestration capacity.

## MATERIALS AND METHODS

### STUDY AREA

Kłodzko County (Fig. 2), located in Lower Silesia, is classified as a Problematic Agriculture Area due to multiple factors affecting agricultural development. The primary constraints include soil erosion, unfavourable agroclimatic conditions, and complex topography, which significantly reduce the economic viability of farming systems. These challenges underscore the need for adaptive land-use strategies and soil conservation practices tailored to the region's diverse physiographic and climatic context, while also enhancing soil organic carbon sequestration. Key limitations include erosion and unfavourable farming conditions, with difficult topography reducing profitability (Jadczyszyn and Smreczak, 2017). Over the past decade, both cultivated land and the number of active farms have significantly declined (BDL, no date), yet the county's humus-rich soils still present substantial potential for organic carbon sequestration and climate change mitigation.

### METHODS

The study followed an integrated research framework, combining spatial data analysis, soil classification, and evaluation of land use compatibility with carbon sequestration potential. The analytical procedure consisted of the following steps.

1. **Acquisition of source materials.** Cartographic data were collected in the form of a detailed soil-agricultural map at a 1:5,000 scale, obtained from the Provincial Land Survey and Cartographic Documentation Center, available in shapefile format (Licence nr MGW-I.7522.67.2024_02_N), serving as the foundational dataset for further spatial analyses within the Kłodzko County (WODGIK, 2024).
2. **Generalisation of soil classification and characterisation of soil structure.** The detailed classification of soils was simplified to the level of soil types. An analysis examined the share and areal distribution of individual soil types. The most common units and their spatial structure were identified to determine the diversity within the study area.
3. **Assessing the sequestration potential of soils**. The analysis was based on two primary soil classification systems: the Polish Soil Classification (SgP, 2019) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). The key criterion for assessing soil carbon sequestration potential was the content of organic carbon in the surface horizons. For certain

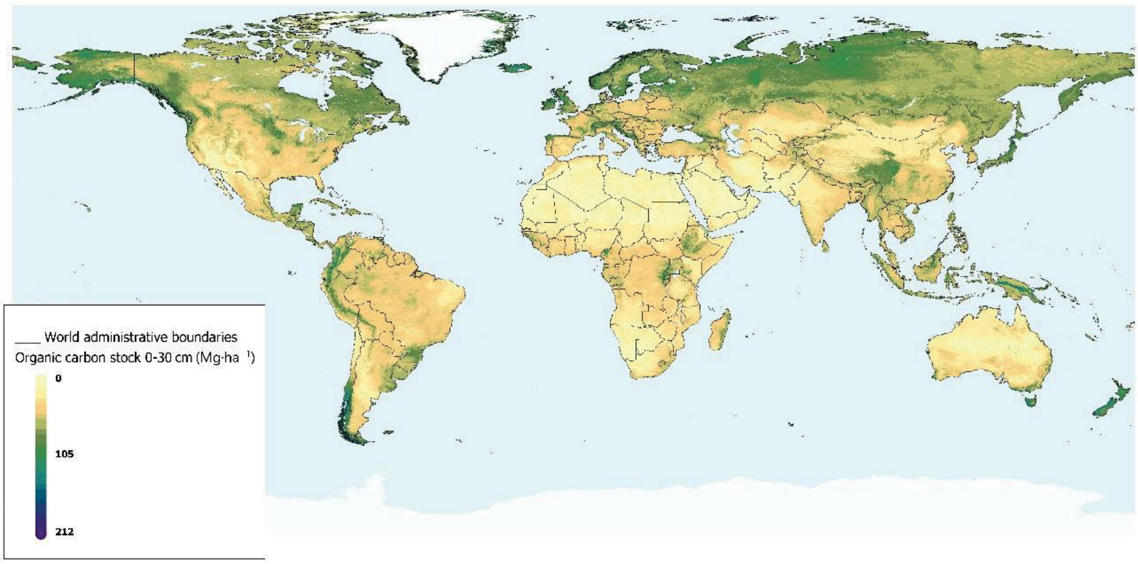


**Fig. 1.** Soil organic carbon (SOC) in the top 30 cm depth; source: Pogio (2020)

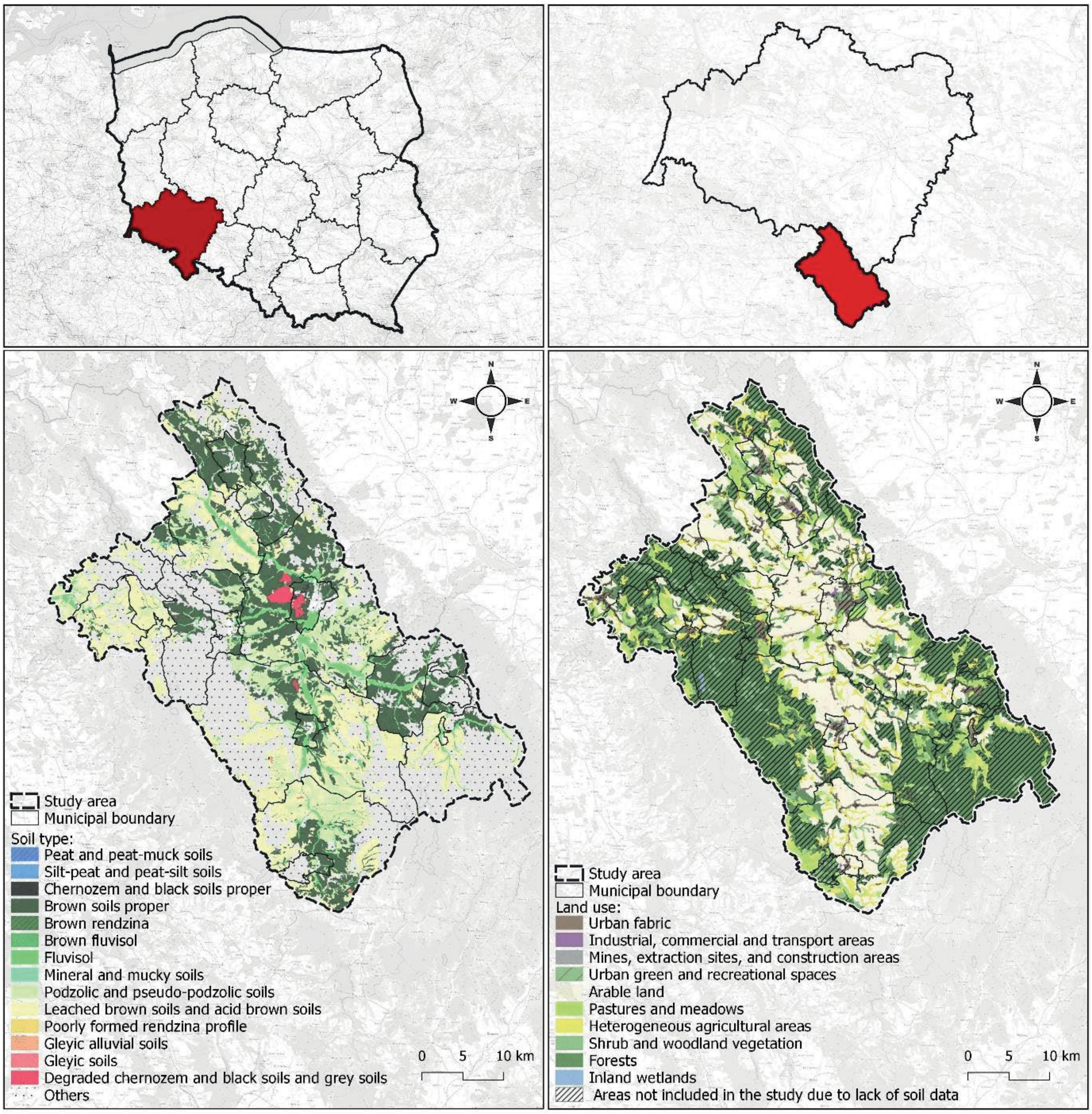


**Fig. 2.** Map of Kłodzko County: location in the context of Poland and Lower Silesia; the county with natural conditions and protected areas; source: own study

soil types whose classification definitions require the presence of a thick and SOC-rich surface horizon, sequestration potential could be determined directly on the basis of these criteria. According to the SgP, 2019 classification, this applies in particular to soils with organic materials (folic, histic, murshic) in the surface horizon containing >12% SOC, and to soils with a thick (>30 cm) mineral surface horizon (arenimurshic, mollic and umbric) with SOC concentrations ranging from >0.6 to <12%. These soil types have been classified as highly or particularly valuable in terms of their capacity to capture and store organic carbon. These include (Kabała *et al*., 2019).

- The most valuable soils that are important for carbon sequestration:
  - o Soil type: Gleby torfowe (Peat soils) – with organic materials,
  - o Soil type: Gleby murszowe (Murshic soils) – with murshic horizon,
  - o Soil type: Gleby limnowe (Limnic soils)
    - – Soil subtype: gleby mułowe (limnic muddy soils) – with organic materials;
- Particularly valuable soils that are important for carbon sequestration:
  - o Soil type: Czarnoziemy (Chernozems), Czarne ziemie (Black earths) – with mollic horizon,
  - o Soil type: Gleby murszowate (Semimurshic soils) – with arenimurshic horizon.

For soils where thickness and SOC content in humus horizons are not key classification criteria, an additional literature review was conducted to assess their carbon sequestration potential. This analysis was necessary due to the lack of system-defined organic surface horizons, which precluded direct classification based solely on typological definitions.

For each soil type, relevant scientific sources were identified that provide information on average organic carbon content in the upper horizons under Polish soil and climate conditions (Tab. S1). These references served as the basis for estimating the sequestration potential of the following soil types:

- Particularly valuable soils that are important for carbon sequestration:
  - o Soil subtype: gleby brunatne właściwe (ordinary brown soils) – assessed based on: Turski (1996); Zawadzki (ed.) (1999); Pikuła (2015),
  - o Soil type: Rędziny brunatne (Brown rendzinas) – assessed based on: Turski (1996); Zawadzki (ed.) (1999); Mocek (2014),
  - o Soil type: Mady brunatne (Brown alluvials) – assessed based on: Zawadzki (ed.) (1999); Mocek (2014); Kobierski and Banach-Szott (2022),
  - o Soil type: Mady właściwe (Ordinary alluvial soils) – assessed based on: Saturnin (1999); Mocek (2014); Kobierski and Banach-Szott (2022);
- Valuable soils that are important for carbon sequestration:
  - o Soil subtype: gleby płowe zbielicowane (podzoilic clay-illuvial soils) – assessed based on: Turski (1996); Zawadzki (ed.) (1999); Brożek and Zwydak (2010),
  - o Soil subtype: brunatne wyługowane (leached brown soils) and brunatne kwaśne (acid brown soils) - assessed based on: Turski (1996); Zawadzki (ed.) (1999); Brożek and Zwydak (2010),
  - o Soil subtype: litosole (lithosols), rędziny inicjalne skaliste (raw rocky rendzinas) – assessed based on: Witek (1973); Turski (1996); Zawadzki (ed.) (1999),
  - o Soil subtype: mady gruntowo-glejowe (gleyic oridnary alluvial soils), mady opadowo-glejowe, (stagnogleyic oridnary alluvial soils) – assessed based on: Witek (1973); Zawadzki (ed.) (1999); Brożek and Zwydak (2010),
  - o Soil type: Gleby gruntowo-glejowe (Gleysols), Gleby opadowo-glejowe (Stagnosols) – assessed based on: Zawadzki (ed.) (1999); Brożek and Zwydak (2010)
  - o Degraded: Czarnoziemy (Chernozems), Czarne ziemie (Black earths), Gleby szare (Grey soils) – assessed based on: Witek (1973); Zawadzki (ed.) (1999); Drozd, Piątek and Łabaz (2007); Łabaz (2010); Smreczak, Jadczyszyn and Skłodowski (2019).

4. **Land use analysis.** Land cover data were sourced from the CORINE Land Cover (CLC) 2018 database, allowing for the identification and spatial assessment of dominant land use forms within the study area.
5. **Assessment of land use–soil compatibility.** Based on literature that was included in Table S2 each land use category was evaluated in terms of its influence on soil carbon sequestration capacity, using a qualitative scale ranging from −2 to +2.
6. **Spatial analysis in QGIS (Quantum Geographic Information System) environment.** Geospatial analysis was performed using QGIS software by overlaying the soil and land cover layers.
7. **Synthesis of results and interpretation.** The integrated analysis identified areas of preserved, partially diminished, and severely degraded sequestration potential, highlighting spatial mismatches between soil-based carbon storage capacity and current land-use patterns.

A key stage of the analysis was the development of a soil carbon sequestration potential assessment scale. To this end, a methodological framework was established to evaluate the relationships among soil types, land cover categories, and their potential contributions to organic carbon sequestration (Fig. 3). The scale was developed based on a review of the relevant literature. The assessment framework comprises several analytical stages, beginning with the classification of soil types according to their capacity to accumulate carbon, followed by the identification of land cover types and their permanence, and concluding with a spatial valorisation process. This final step helps to identify areas with high, medium, and low carbon sequestration potential.

## SOILS

Kłodzko County, located within the Kłodzko Basin in the Lower Silesian Voivodeship of southwestern Poland, is characterised by high lithological diversity and complex land relief. Combined with local climatic conditions, these factors have shaped a mosaic of soils differing in origin and properties (Bobiński *et al.*, 2004). The soil characteristics of Kłodzko County are based on the soil-agricultural map, which provides detailed information on soil types, subtypes, land-use classes, and key soil properties. However, this dataset covers only approximately 60% of the county's territory, as soils beneath forests and fully urbanised zones were not surveyed due to the absence of publicly available vector data suitable for spatial analysis and visualisation. The

| | | | | |
|---|---|---|---|---|
| The most valuable soils that are important for carbon sequestration | 2 | 0 | -2 | -2 |
| Particularly valuable soils that are important for carbon sequestration | 2 | 0 | -1 | -2 |
| Valuable soils that are important for carbon sequestration | 2 | 0 | -1 | -2 |
| Heavily degraded soils in need of reclamation, but important for carbon sequestration | 2 | 0 | 0 | -2 |
| 2 Full (completely preserved) potential of soils for sequestration<br>1 Partially preserved potential of soils in $CO_2$ sequestration<br>0 Impossible to determine precisely, dependent on detailed use<br>-1 Partially lost potential of soils in $CO_2$ sequestration<br>-2 Completely lost potential of soils in $CO_2$ sequestration | **GOOD**<br>Pastures and meadows;<br>Forests;<br>Shrub and woodland vegetation | **DIFICULT TO DETERMINE**<br>Heterogeneous agricultural areas;<br>Urban green and recreational spaces | **BAD**<br>Arable land | **THE WORST**<br>Urban fabric industrial, commercial and transport areas;<br>Mines, extraction sites, and construction areas |

**Fig. 3.** The process of evaluating the use of carbon sequestration potential; source: own study

most recent vector-format dataset for county soils dates back to 2010, and the underlying soil map was prepared in accordance with the Polish Soil Classification System of 1959 (PTG, 1959; Witek, 1974; Jadczyszyn and Smreczak, 2017).

To facilitate data interpretation, a tabular comparison aligns the archival classification with the current Polish Soil Classification (Kabała *et al.*, 2019) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022). This comparative approach enables an assessment of historical and contemporary classification frameworks. The analysis (Tab. S1) focuses on organic matter content and humus horizon thickness, which are crucial for evaluating soil carbon sequestration potential. The table includes a final assessment of soils concerning their role in carbon accumulation and long-term storage capacity (Świtoniak *et al.*, 2019).

Soils in Kłodzko County display high diversity due to geomorphological and hydrological conditions, resulting in varying potential for organic carbon sequestration. The most abundant carbon stocks occur in peat, murshic, and limnic muddy soils, which contain significant amounts of organic matter and high levels of $C_{org}$, reaching up to several percent. Equally favourable are chernozems and black-earths, characterised by thick, humus-rich surface horizons.

Brown soils, brown rendzinas, or alluvial soils, especially under permanent grassland, also show high carbon content. By contrast, leached brown soils, Gleysols, and initial soils contain less organic matter and are weaker carbon stores, particularly in areas with unfavourable moisture conditions. Degraded soils that have lost humus properties through intensive use or erosion have the lowest carbon accumulation capacity and require targeted restoration approaches to improve their ecological functions.

Although the complex topography of the area has an impact on a wide variety of soils, the dominant soil units in Kłodzko District are brown soils (ordinary, leached, and acid subtypes), podzolic clay-illuvial soils, and ordinary alluvial soils. The spatial distribution of soil units is highly fragmented, with many small patches reflecting high pedodiversity (Fig. 4). Ordinary brown, leached, and acid brown soils are most common in these smaller units. Larger homogeneous units (>500 ha) are rare and associated with specific geomorphological features. Carbon sequestration potential is moderate, influenced by mineral soils with varying humus content and biological activity. Local heterogeneity leads to spatial differences in carbon stabilisation, emphasising the need for conservation strategies tailored to site-specific soil conditions.

The distribution of soil categories in Kłodzko County indicates a high potential for carbon sequestration, with particularly valuable soils covering 48.3% of the area and soils of medium importance accounting for 50.6%. However, the presence of heavily degraded soils (1%) underscores localised constraints that may affect the overall efficiency of carbon storage.

## LANDUSE

The land cover classification was based on the Corine Land Cover (CLC) system (Copernicus Services, no data). As soil data were unavailable for forested and urbanised areas, almost 40% of the area was excluded from calculations; thus, only the area with available soil data (about 60% of Kłodzko District) was analysed. The results highlight a dominance of arable land (48.2%) and pastures and meadows (15.4%). Forest and heterogeneous agricultural area are less prevalent, each covering nearly 14%. (Fig. 5). Urban and industrial land, including transport infrastructure and extraction sites, collectively accounts for a marginal proportion of the land cover.

After the initial data evaluation, the final step was a merger evaluation. Each soil–land use combination was assigned a score from −2 to +2 (Tab. S2), reflecting its influence on carbon

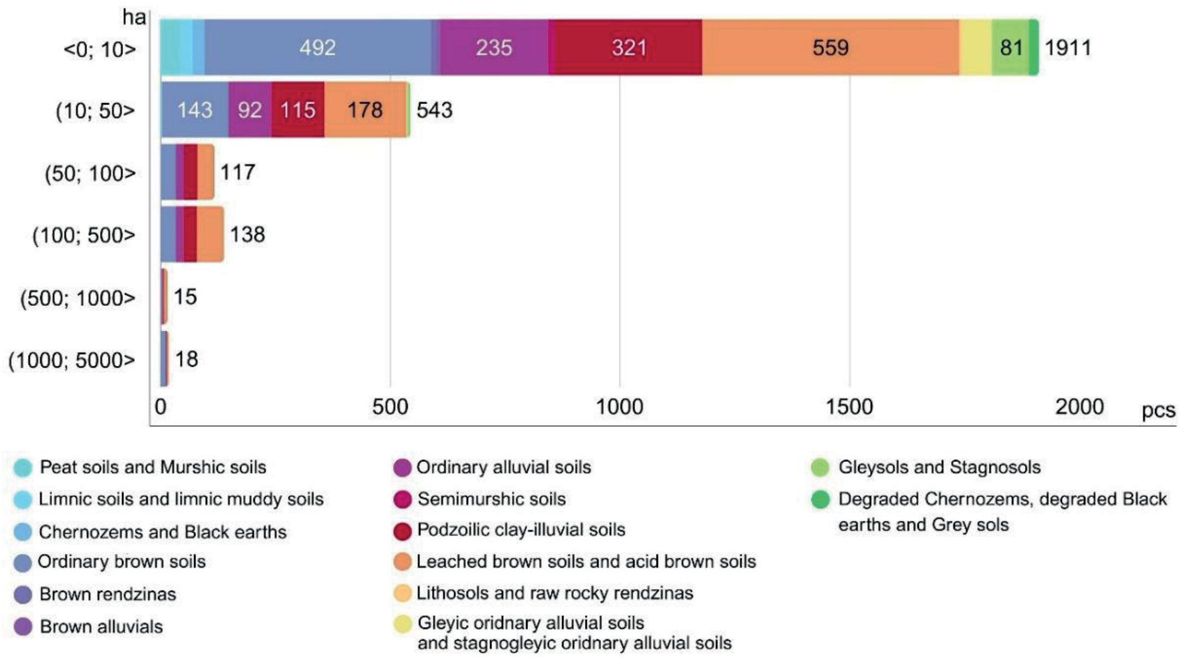


**Fig. 4.** Histogram of soil surface areas in the analysed part of Kłodzko District; the *Y* axis represents area classes of individual soil patches (ha), while the *X* axis represents the number of soil patches within each class; source: own study

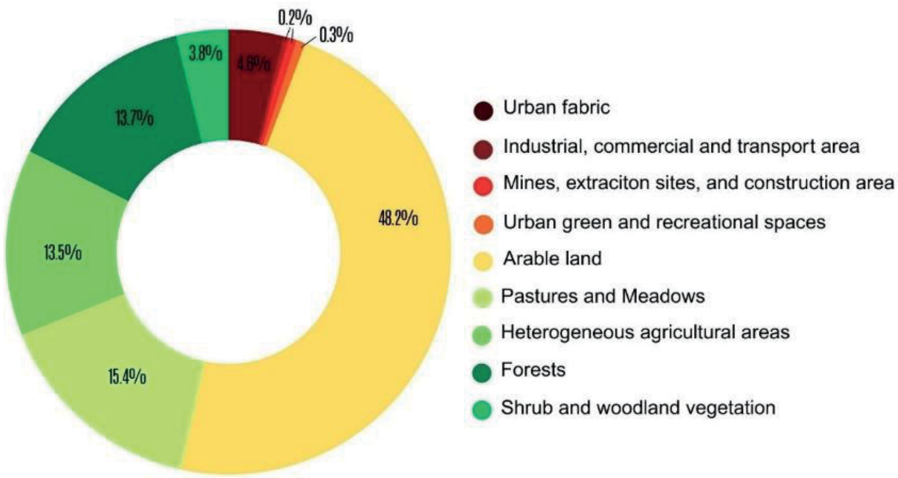


**Fig. 5.** Land use of the analysed fragment of Kłodzko County; source: own study

storage. This method was based on existing scientific literature and established criteria, ensuring a systematic and evidence-based evaluation (Rooney *et al.*, 2014; Mengist, Soromessa and Legese, 2020). Vector layers representing soil types and land cover were overlaid, and spatial intersections generated to identify all unique combinations. This procedure ensured a comprehensive analysis of soil–land use relationships and enabled the assignment of impact scores to each unique soil–land use combination at the local scale.

## RESULTS

The analysis of soil and land-use data revealed significant correlations between soil typology, land cover, and soil organic carbon (SOC) sequestration potential within the selected municipality. Literature-based classification demonstrated that high-organic-content soils, including organic soils, alluvial formations, and chernozems, exhibit elevated carbon storage capacity, particularly when management practices facilitate continuous organic matter input with minimal disturbance.

Spatial correlation between soil types and current land use identified extensive areas with medium-to-high sequestration potential that are constrained by land cover classification inhibiting soil organic carbon (SOC) accumulation, primarily impervious surfaces, developed zones, and intensively managed arable land. The pie chart (Fig. 6) illustrates that only 20.5% of soils in Kłodzko County retain their full sequestration potential, and an additional 2.7% retain it partially, typically under semi-natural or extensive land uses such as forests and grasslands. However, 59.3% of the discussed area shows a partial loss of sequestration potential, primarily due to suboptimal land use practices such as intensive agriculture. More critically, 7.2% of the study area demonstrates a complete loss of sequestration function, typically linked with sealed and built-up surfaces where soils are no longer biologically or chemically active. Furthermore, for the remaining 10.3%, the status could not be clearly determined due to ambiguous or heterogeneous land cover, requiring site-specific verification.

The spatial distribution of soil carbon sequestration potential in Kłodzko County highlights significant variation across the region. Areas with lost or partially lost potential dominate the central and northern zones, primarily due to urban development and intensive agriculture. In contrast, preserved sequestration potential is mainly found in forested and less transformed landscapes, particularly in the south and west. This spatial pattern reveals a disconnection between natural soil capacity and current land use, underscoring the need for soil-aware spatial planning.

Spatial correlation between soil types and current land use identified substantial areas with medium-to-high sequestration potential now occupied by land cover classes that inhibit SOC accumulation, primarily impervious surfaces, developed zones,

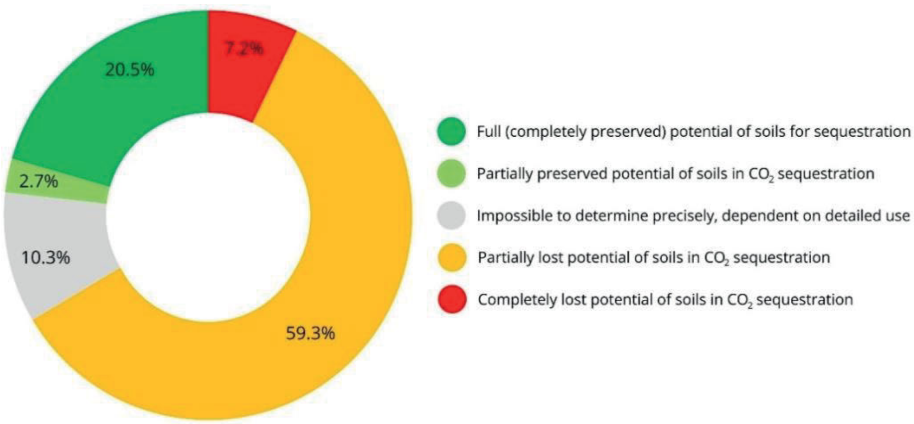


**Fig. 6.** The percentage of loss of carbon sequestration potential; source: own study

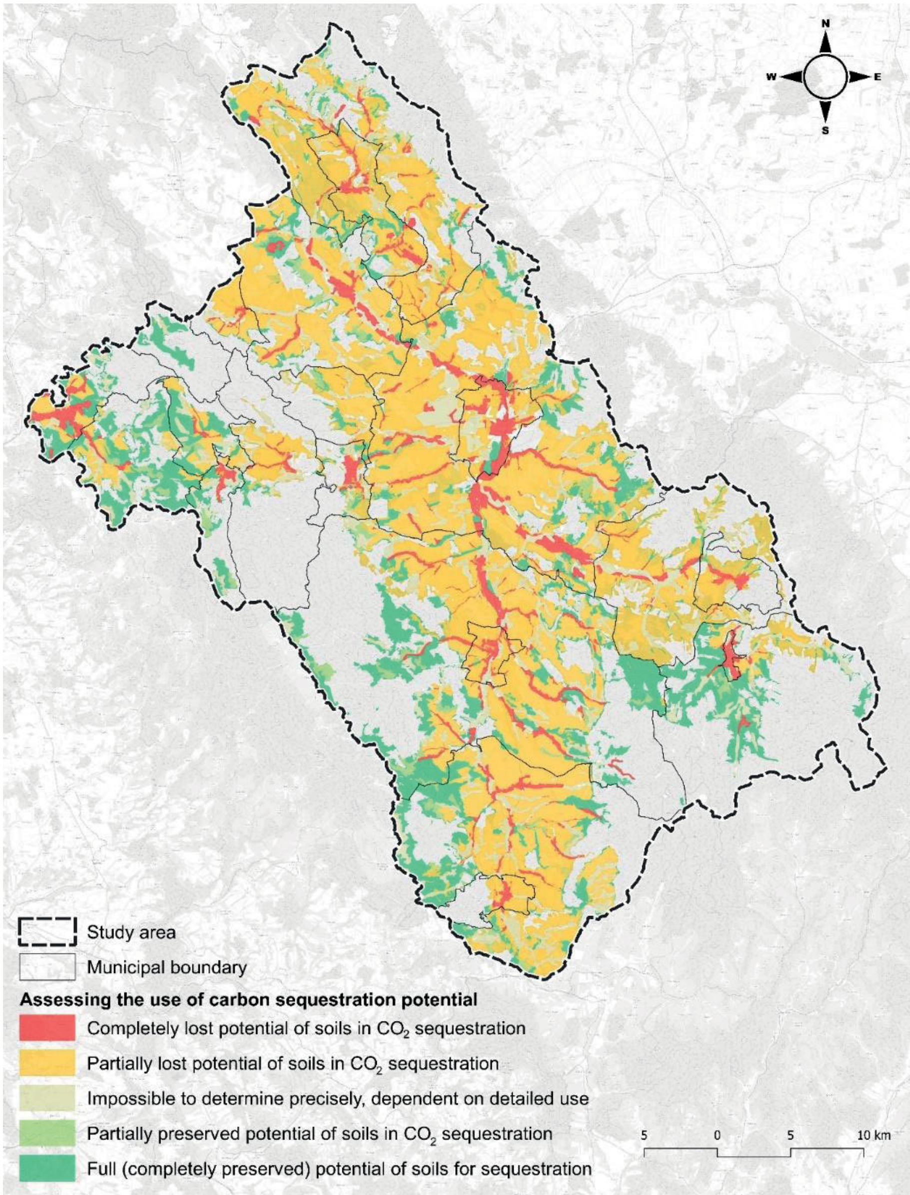


**Fig. 7.** Spatial distribution of loss of soil carbon sequestration potential; source: own study

and intensively managed arable land (Fig. 7). This spatial incongruence between pedological characteristics and anthropogenic land-use patterns indicates systematic degradation of carbon sequestration capacity, attributable to urbanisation and non-ecological land transformations.

The methodological framework, based on open-access cartographic resources and qualitative assessment criteria, effectively identified zones experiencing diminished ecological functionality. The results show that a considerable part of Kłodzko County is experiencing a progressive decline in carbon retention capacity due to misalignment between soil capacity and land use.

## DISCUSSION

The spatial incongruence between pedological characteristics and anthropogenic land-use patterns reveals a systemic degradation of soils' carbon-storage function. Urban expansion and non-ecological land transformations disproportionately affect soils rich in organic matter, compromising their capacity to provide climate-regulating ecosystem services. This highlights a governance gap, as soil functionality remains insufficiently integrated into land-use planning and decision-making (Fu *et al.*, 2015; Sylla, 2023; Woźniak *et al.*, 2024).

This mismatch reflects broader structural inefficiencies in spatial governance. Current legal instruments often prioritise arable productivity indices while neglecting ecological functions of non-agricultural soils, particularly those rich in organic matter. As a result, soils of high ecological value that are not classified as agriculturally strategic remain vulnerable to degradation. Addressing this requires reframing soil carbon research and policy from a focus on micro-level agricultural practices toward broader land-use patterns (Ociepa-Kubicka, 2014).

Methodologically, the approach – based on publicly available datasets – serves as a practical screening and policy-prioritisation tool, strengthening Strategic Environmental Assessment by embedding soil carbon considerations at the planning stage (Tokarczyk-Dorociak *et al.*, 2019). Its interpretation is constrained by incomplete spatial coverage (notably forested and heavily urbanised zones), reliance on generalised proxies (organic carbon content, humus horizon thickness), and a qualitative, literature-based assessment of land-cover impacts. These limitations indicate clear priorities for refinement: expanding spatial data coverage, integrating targeted field measurements and monitoring to calibrate sequestration estimates, and testing alignment with national valuation and classification frameworks to address potential misclassification biases. Such empirical improvements would increase the method's precision and policy relevance for climate-responsive land management.

## CONCLUSIONS

The analysis demonstrates a pronounced spatial mismatch: soils with high carbon-sequestration potential are frequently subjected to land uses that degrade their ecological function, revealing a systemic planning vulnerability that undermines climate mitigation and resilience goals. Addressing this requires making soil carbon an explicit criterion in spatial planning and Strategic Environmental Assessment. This should be supported by operational measures such as systematic mapping of high-carbon soils, integrating these maps into zoning and land-use regulations, and adopting protective designations or land-use restrictions for priority carbon stocks. The proposed standardised index offers a practical screening tool for policy prioritization, with its utility expected to grow through expanded spatial coverage, field validation, and harmonisation with national valuation and classification systems. Effective implementation will also depend on capacity building for planners and stakeholders, the development of incentives or compensation mechanisms for conservation, cross-sectoral governance to reconcile productivity with ecological functions, and establishment of monitoring and reporting protocols to track soil-carbon changes over time. Collectively, these steps would support more climate-responsive land management and help preserve critical soil ecosystem services.

## SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_66_Wisniewska.pdf.

## CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

## INSTITUTIONAL REVIEW BOARD STATEMENT

This study is independent research and did not receive financial support.

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