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SPATIAL DELINEATION OF PEDOGENETIC ENVIRONMENTS AND IMPLICATIONS FOR SOIL ORGANIC CARBON MANAGEMENT IN THE BANAT PLAIN, WESTERN ROMANIA

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Abstract. *The Banat Plain, located in western Romania, includes a highly diverse mosaic of geomorphological, lithological and hydrological environments that generate contrasting pathways of soil formation and, consequently, different capacities for organic matter accumulation and stabilization. This study develops a preliminary spatial framework for a future doctoral investigation focused on soil organic carbon (SOC) dynamics. The objectives were to delineate representative pedogenetic environments, identify the dominant soil-forming processes and discuss their potential implications for SOC storage, vulnerability and sustainable management. The methodological approach integrated pedological, geomorphological, hydrological, climatic and land-use information and organized the plain into representative sectors reflecting high, transitional, low and alluvial settings. Particular attention was given to bioaccumulation and humification, gleying and stagnogleying, vertic processes, salinization/sodification and eluviation–illuviation. The preliminary network comprises ten representative sectors, with a deliberate emphasis on low-plain environments because of their pronounced drainage contrasts and the occurrence of hydromorphic, vertic and salt-affected soils. The synthesis indicates that SOC behaviour cannot be interpreted independently of pedogenesis: waterlogging may slow organic matter mineralization, fine-textured and shrink–swell materials may enhance physical protection of organic matter, while drainage changes, warming, drought and intensive cultivation may accelerate carbon losses. The proposed framework therefore links soil classification and landscape position with future SOC measurements, bulk density, profile depth and geospatial analysis. It provides a scientifically grounded basis for subsequent field sampling, GIS integration and the development of differentiated soil-carbon management strategies for the Banat Plain.*

Keywords: *Banat Plain; pedogenetic environments; soil organic carbon; soil organic matter; hydromorphism; sustainable soil management*

INTRODUCTION

Soil is a fundamental component of terrestrial ecosystems and agricultural production, simultaneously regulating water and nutrient cycles, supporting biological activity and storing large quantities of carbon. Soil organic carbon (SOC), the carbon component of soil organic matter (SOM), is therefore closely related to soil fertility, aggregate stability, water retention and resilience to climatic and anthropogenic pressures. At the regional scale, SOC stocks reflect the balance between organic inputs and losses through decomposition, erosion, leaching and redistribution, while their persistence is strongly influenced by texture, mineralogy, aggregation, hydrological regime, climate and land use (WIESMEIER et al., 2019; YANG et al., 2020; WENZEL et al., 2022).

The importance of SOC has increased in the context of climate change and the search for land-management strategies capable of simultaneously sustaining agricultural productivity and enhancing carbon sequestration. Recent studies emphasize that increasing SOC cannot be approached as a uniform technological objective, because the attainable stock and the stability of newly accumulated carbon depend on the intrinsic properties of each soil and on the environmental setting in which the soil developed (GUILLAUME et al., 2022; BÜCHI et al., 2022).

Thus, the same management practice may generate different outcomes in a Chernozem, a Vertisol, a Gleysol or a salt-affected soil, even under comparable cropping systems.

The Banat Plain is particularly suitable for analysing these relationships because it includes a strong contrast between higher, better-drained surfaces and lower subsident sectors affected by shallow groundwater, temporary water stagnation and, locally, salt accumulation. Its landscape is part of the eastern Pannonian sedimentary domain and is characterized by alluvial and loess-like deposits, weak regional slopes and a dense hydrographic and drainage network. Climatic studies in western Romania also indicate increasing temperature and changes in water availability for crops, factors that can modify both soil moisture regimes and the decomposition of organic matter (ȘMULEAC et al., 2020).

From a pedogenetic perspective, the plain contains environments favourable to bioaccumulation and humification, but also areas where gleying, stagnogleying, vertic processes, salinization/sodification and eluviation–illuviation become dominant. These processes have direct or indirect implications for SOC. Water saturation can restrict oxygen diffusion and reduce mineralization rates, whereas alternating wet–dry conditions can intensify aggregate formation and disruption. Fine-textured shrink–swell materials may contribute to the physical protection and redistribution of organic matter, while sodification and salinization can alter aggregate stability, hydraulic conductivity and microbial activity (AMENDOLA et al., 2018; KOVDA, 2020; OLIVEIRA FILHO et al., 2020; SINGH, 2021).

For this reason, a robust assessment of SOC in the Banat Plain should begin with a clear spatial delineation of pedogenetic environments rather than with undifferentiated sampling. The present paper represents the preliminary spatial and conceptual stage of a broader doctoral research programme. Its aim is to delineate representative pedogenetic environments within the Banat Plain, identify the dominant soil-forming processes, and establish their expected relevance for SOC accumulation, stabilization and loss. The novelty of the approach lies in integrating landscape position, drainage, parent material and pedogenesis into a practical framework for future SOC quantification and for the development of differentiated strategies of soil organic matter and carbon management.

MATERIAL AND METHODS

Study area and conceptual delimitation

The study area is the Banat Plain in western and south-western Romania. The plain is characterized by low regional gradients and by a marked contrast between relatively elevated surfaces, transitional sectors, low subsident plains and alluvial environments. The preliminary delimitation was based on the spatial correlation of geomorphological position, surface deposits, drainage conditions, hydrographic setting, climatic context, land use and known pedological characteristics. This approach follows the principle that soil distribution is controlled by interacting soil-forming factors and that the interpretation of SOC should be linked to the pedogenetic environment rather than to a single soil property.

Documentary sources and spatial criteria

The synthesis used existing pedological and geomorphological information, hydrographic and groundwater data, climatic information and land-use evidence relevant to the Banat Plain. The spatial criteria used to differentiate sectors were: relative elevation and landscape position; expected drainage and groundwater influence; dominant parent-material texture; occurrence of alluvial or loess-like deposits; and the expected expression of diagnostic pedogenetic processes. The resulting framework is intended for subsequent integration in a GIS

database in which soil profiles, laboratory results, climatic variables and land-use information can be analysed jointly.

Selection of representative sectors and pedogenetic processes

Ten representative sectors were selected to cover the main geomorphological and pedohydrological contrasts of the plain. Their distribution intentionally gives greater weight to low-plain environments, where hydromorphism, vertic properties and salinity-related processes are most likely to interact. For each sector, the dominant or potentially diagnostic pedogenetic processes were identified from landscape position, drainage and available soil information. The classification of processes included bioaccumulation/humification, argillization and eluviation–illuviation, gleying and stagnogleying, vertic processes, salinization/sodification and local erosion or redistribution.

Framework for subsequent SOC assessment

The spatial framework is designed to support subsequent field investigations using soil profiles and auger observations. Morphological description will follow the Romanian System of Soil Taxonomy and will be correlated with the World Reference Base for Soil Resources. Future laboratory measurements will include SOC concentration, bulk density, texture, pH, carbonates and selected hydrophysical indicators. SOC stocks will be calculated for defined depth intervals by combining SOC concentration, bulk density and layer thickness, with correction for coarse fragments where necessary. The present paper does not report measured SOC stocks; instead, it establishes the pedogenetic stratification required for a statistically and functionally representative sampling design.

RESULTS AND DISCUSSION

Environmental controls on soil differentiation

The preliminary synthesis confirms that relief and water regime are the primary landscape controls on soil differentiation in the Banat Plain. Higher sectors are generally better drained and favour the development of humus-rich surface horizons and relatively stable aeration conditions. By contrast, low-lying and subsident sectors are more frequently affected by shallow groundwater or temporary stagnation of precipitation water. These contrasts generate short-distance transitions from well-aerated pedogenetic environments to hydromorphic environments, which is a key reason for adopting a stratified rather than uniform sampling approach.

Lithology reinforces this spatial differentiation. Alluvial and loess-like deposits vary in particle-size distribution, and the occurrence of fine, clay-rich materials promotes low permeability, shrink–swell behaviour and water stagnation. Coarser alluvial materials generally favour faster drainage and stronger aeration. Since the fine mineral fraction is one of the main controls on SOC stabilization through organo-mineral associations, this lithological diversity is expected to produce important differences in both SOC concentration and persistence (WIESMEIER et al., 2019; WENZEL et al., 2022).

Climate introduces a further dynamic control. Warmer conditions can accelerate decomposition when sufficient moisture is available, whereas drought can restrict biological activity and plant-derived carbon inputs. In the Banat Plain, the increasingly variable availability of water for crop production documented by ȘMULEAC et al. (2020) is particularly relevant because it interacts with soil texture and drainage. Consequently, climatic effects on SOC are expected to differ between well-drained Chernozem-like environments, clay-rich Vertisol environments and hydromorphic lowlands.

Table 1

Major pedogenetic processes and their expected relevance to soil organic carbon in the Banat Plain

Pedogenetic process	Main environmental controls	Typical soil effect	Potential relevance to SOC
Bioaccumulation and humification	Organic inputs; vegetation; balanced aeration	Humus-rich A horizons; aggregate development	Promotes SOC accumulation and nutrient retention
Gleying	Shallow groundwater; prolonged saturation	Reducing conditions; Fe/Mn redistribution	May slow decomposition and favour SOC preservation
Stagnogleying	Temporary perched water; low permeability	Seasonal redox features; poor aeration	Modifies mineralization and can increase spatial SOC variability
Vertic processes	Clay-rich parent material; wet–dry alternation	Shrink–swell; cracking; pedoturbation	Can redistribute and physically protect organic matter
Salinization / sodification	Mineralized water; evaporation; poor drainage	Salt accumulation; dispersion; low permeability	May alter microbial activity and destabilize structure
Eluviation–illuviation	Percolating water; textural differentiation	Vertical redistribution of clay and fine material	May transfer organo-mineral C to subsoil horizons
Erosion / redistribution	Runoff; tillage; microrelief	Removal and deposition of fine soil material	Can cause local SOC losses and depositional SOC accumulation

Dominant pedogenetic pathways and implications for SOC

Bioaccumulation and humification are expected to dominate on the better-drained sectors where plant-derived carbon enters an aerated mineral matrix. In these environments, the long-term maintenance of SOC depends strongly on the balance between residue inputs, tillage intensity, fertilization and aggregate protection. Evidence from agricultural soils shows that management modifies not only total SOC but also the distribution and stability of organic-carbon fractions (AUDETTE et al., 2021; BÜCHI et al., 2022). This supports the need to interpret future SOC measurements together with management history.

Hydromorphism represents the most widespread contrasting pathway in the low plain. Gleying and stagnogleying are associated with oxygen limitation, redox oscillations and reduced decomposition rates during saturated periods. A global analysis of hydromorphic soils showed that increasing hydromorphy is generally associated with higher SOC concentrations, although the response is conditioned by climate, texture and mineral composition (AMENDOLA et al., 2018). In the Banat Plain, drainage infrastructure and groundwater fluctuations may therefore create both SOC-preserving and SOC-loss conditions: drainage can improve agricultural workability but may also increase aeration and organic-matter mineralization.

Vertic processes are also particularly important in the lower and transitional plains. Shrink–swell cycles produce cracking, pedoturbation and strong structural rearrangement. Vertisols can display large spatial and temporal variation in water availability and mechanical behaviour, while their high clay content may favour organo-mineral protection of carbon (KOVDA, 2020). However, intensive tillage performed outside the optimum moisture range can accelerate structural degradation and modify the physical protection of SOM. This makes vertic environments a priority for monitoring bulk density, aggregation and SOC by depth.

Salinization and sodification occur locally where mineralized waters, restricted drainage and evaporation interact. Sodium-induced dispersion can reduce hydraulic conductivity and structural stability, and may also modify organic-matter mobility and microbial processes (OLIVEIRA FILHO et al., 2020).

Preliminary spatial research network

Table 2

Representative sectors selected according to geomorphological setting and dominant pedogenetic processes

Point	Representative sector	Geomorphological setting	Processes / conditions targeted
P1	Tormac	High plain	Bioaccumulation; argillization
P2	Gătaia	High plain	Bioaccumulation; argillization; local hydromorphism
P3	Percosova–Butin	Gătaia Plain	Drainage and lithological variability
P4	Deta–Denta	Transition plain	Gleying; stagnogleying
P5	Opatița–Berecuța	Low plain	Vertic processes; hydromorphism
P6	Banloc–Livezile	Low plain	Hydromorphism; salinization / alkalization
P7	Ciacova	Low plain	Gleying; stagnogleying; salinization
P8	Diniaș–Foeni	Low plain	Gleying; vertic processes; salinization
P9	Timiș Plain	Alluvial plain	Gleying; stagnogleying
P10	Aranca Plain	Low plain	Vertic processes; gleying; salinization

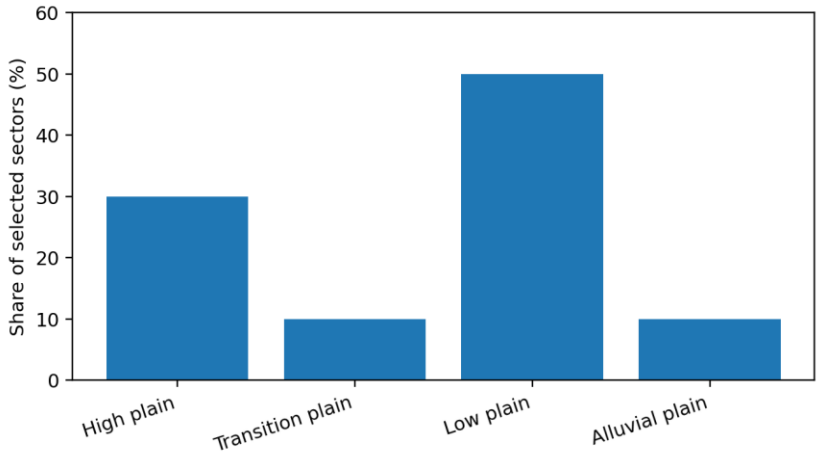


Figure 1. Distribution of the representative study sectors by geomorphological setting

Although these areas may occupy smaller surfaces than the main agricultural soils, they are important because they represent high-vulnerability pedogenetic environments where SOC management cannot be separated from water and salt management. Modern approaches to salinity management increasingly combine drainage, soil amendments, remote sensing and GIS (SINGH, 2021).

The distribution of the ten sectors deliberately emphasizes the low plain (50% of the network), while high-plain environments account for 30%, and transitional and alluvial sectors

each account for 10%. This asymmetry is methodologically justified rather than proportional to surface area: low-plain environments contain the strongest gradients in drainage, clay content, hydromorphism and salinity, and therefore the greatest expected variability in carbon stabilization and loss. The network is designed to capture process contrasts, not merely geographic coverage.

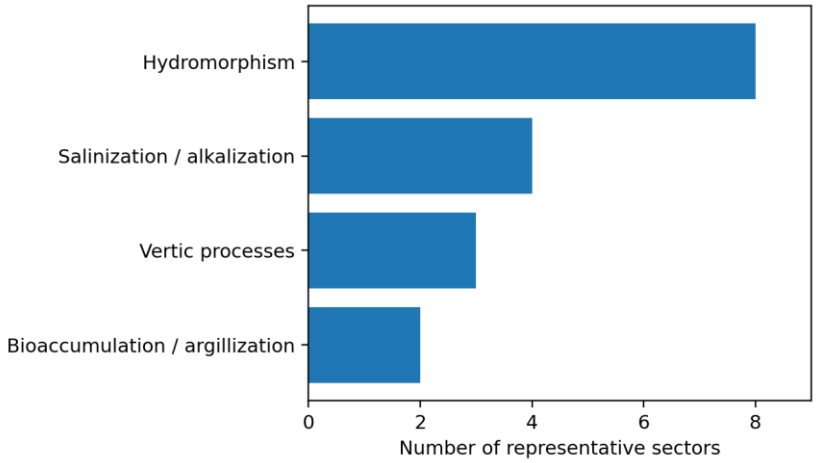


Figure 2. Frequency of the main pedogenetic processes represented in the preliminary research network

Hydromorphism is represented in eight of the ten sectors, salinization/alkalization in four, vertic processes in three, and bioaccumulation/argillization in two. The predominance of hydromorphic conditions reflects the importance of groundwater and drainage in the Banat lowlands. From the perspective of SOC research, this distribution is advantageous because it allows the future dataset to test whether water saturation and redox conditions produce systematically different SOC stocks and depth distributions from those observed in well-drained soils.

SOC accumulation, vulnerability and management perspectives

The proposed pedogenetic stratification has direct management relevance. SOC storage is not determined solely by the amount of organic residues added to soil; it also depends on the capacity of mineral surfaces and aggregates to stabilize carbon and on the environmental controls of decomposition. Fine-textured soils may have a higher capacity for mineral-associated carbon, but that capacity is not unlimited and may differ strongly between soil groups and land uses (GUILLAUME et al., 2022; WENZEL et al., 2022). Consequently, management strategies should be differentiated according to the pedogenetic environment and the existing SOC status rather than applied uniformly across the plain.

On well-drained agricultural soils, maintaining or increasing SOC requires a sustained balance of carbon inputs and reduced losses. Crop rotations, cover crops, residue retention, organic amendments and reduced soil disturbance can support aggregation and SOC accumulation, but their effect depends on the baseline soil condition and climate. Long-term experiments and recent synthesis studies show that conservation-oriented management can improve SOC and soil health, particularly when combined with residue return and diversified input strategies (NARESH et al., 2024; TENG et al., 2024).

In hydromorphic and vertic sectors, the priority is to integrate carbon management with water management and soil physical protection. Excessive drainage may accelerate mineralization, whereas inadequate drainage restricts root development and trafficability. Similarly, heavy clay soils require strict control of tillage timing to avoid compaction and structural damage. These interactions illustrate why SOC should be regarded as both a biogeochemical indicator and a management target. Recent research increasingly treats carbon sequestration in agricultural soils as a component of climate mitigation and farm resilience, but emphasizes the need for robust monitoring and spatially explicit baselines (FRANK et al., 2024; NEUENKAMP et al., 2024).

For the Banat Plain, the principal scientific contribution of the proposed framework is therefore the connection between classical pedology and contemporary carbon management. Instead of treating SOC as an isolated laboratory variable, the research will interpret it in relation to soil genesis, profile morphology, hydrological regime, landscape position and land use. This approach can distinguish sites with high natural carbon-retention capacity from sites where SOC is more vulnerable to drainage, drought, structural degradation or intensive cultivation. It can also support the identification of realistic management options for increasing SOM without compromising the specific physical and hydrological requirements of each soil environment.

CONCLUSIONS

The Banat Plain is not a uniform pedological environment. Its higher, transitional, low and alluvial sectors differ in parent material, drainage and groundwater influence, generating contrasting pedogenetic processes that are directly relevant to soil organic carbon dynamics.

The preliminary spatial framework identifies bioaccumulation and humification, gleying and stagnogleying, vertic processes, salinization/sodification and eluviation–illuviation as the main process groups that should be explicitly considered when interpreting SOC. Hydromorphism has the broadest representation in the proposed network, reflecting the major role of the water regime in the low plain.

The expected relationship between pedogenesis and carbon is process-dependent: well-drained humus-rich environments favour biological inputs and aggregate formation; prolonged saturation can reduce mineralization; clay-rich vertic environments can provide strong physical and mineral protection but are vulnerable to structural degradation; and salt-affected environments require the integration of carbon, water and salinity management.

The proposed ten-sector network provides a scientifically justified basis for the subsequent doctoral research stage, in which SOC concentration, bulk density, profile depth, soil physical and chemical properties, climate and land use will be integrated in a GIS framework. This will permit the calculation and spatial comparison of SOC stocks and the identification of zones with contrasting carbon-storage potential or vulnerability.

From an applied perspective, the study supports a differentiated concept of sustainable soil management in which the conservation or accumulation of organic carbon is adapted to the pedogenetic environment. Such an approach can contribute to maintaining fertility, reducing degradation, improving resilience to climatic variability and increasing the capacity of agricultural soils in the Banat Plain to provide carbon-storage and other ecosystem services.

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