Original Scientific paper
10.7251/AGREN2503069P
UDC 631.4:543.632.42(497.7)

SOIL ORGANIC CARBON VARIABILITY IN BULGARIAN SOILS

Kristiyan PANAYOTOV[1*], Matthew Tom HARRISON[2]

[1]Climate, Atmosphere and Water Research Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria
[2]Tasmanian Institute of Agriculture, University of Tasmania, Newnham Drive, Launceston, TAS, Australia
*Corresponding author: kristiyanpanayotov@gmail.com

ABSTRACT

Comprehensive assessments of soil organic carbon (SOC) across Bulgarian arable lands are scarce. In this study, we quantify and map SOC variability in the country's primary grain-producing regions using a stratified sampling approach and geospatial analysis. A total of 1,287 composite topsoil samples (0–30 cm) were collected during winter 2022–2023 from homogeneous management zones outlined with FAO-WRB soil classes and national survey layers. Samples were analyzed for organic carbon via dry combustion (ISO 10694). Spatial aggregation (feature binning) and mapping showed that SOC concentrations ranged from 0.8% to 4.4% (mean 1.9%, SD 0.44%). Distinct regional contrasts were also uncovered, where several southeastern municipalities exhibited low SOC (≤1.0–1.2%), while northwestern localities reached >4%. There were discernible SOC differences between soil types. For example, Luvisols tended to contain less SOC than Kastanozems and Vertisols, which could be expected based on textural and hydrological restrictions. The resulting maps highlight areas potentially vulnerable to degradation and offer baselines for targeted management improvement (e.g., residue retention, cover crops, reduced tillage) and policy design. Given the single-season snapshot and topsoil focus, we recommend a subsequent time series and inclusion of deeper layers and equivalent-soil-mass approaches for stock estimation. We provide one of the first high-resolution SOC datasets for Bulgarian arable regions and present actionable evidence to support climate-smart and resilient farming systems.

Keywords: *soil organic carbon, geospatial analysis, grain-production, soil sampling.*

INTRODUCTION

Soil organic matter is a key factor in soil health, influencing soil structure, nutrient availability, biological activity, and water retention (Henry et al. 2022; Kabir et al. 2024). It has also been recognized that increasing soil organic carbon (SOC) levels is crucial for mitigating climate change. Agricultural practices significantly impact SOC content, either by increasing carbon inputs or by accelerating decomposition and, consequently, loss of organic matter. In this context, intensive agricultural management has resulted in substantial SOC depletion (Panagos et al., 2015), leading to reduced soil fertility and productivity (McDonald et al. 2023).

In response to the climate crisis, the 4-per-mille initiative (launched at COP21) highlights the critical role that SOC sequestration can play in efforts to mitigate climate change. The initiative proposes an annual increase of 0.4% in global SOC stocks to offset CO_2 emissions (Rumpel et al., 2018). In line with this vision, carbon farming has evolved, promoting practices aimed at enhancing carbon storage in soils, reducing greenhouse gas emissions, and protecting existing carbon reserves (Van Hoof, 2023).

SOC measurement is essential as it provides a fundamental perspective on soil health and the potential for carbon sequestration (Six et al., 2002). Such assessments require accurate measurement of carbon concentration (per volume of soil) and SOC spatial distribution, forming a basis for effective soil management practices and achieving sustainable agriculture goals (Don et al., 2011). To conduct this accurately, the density of the samples is critical. Insufficient sampling misrepresents spatial variability, resulting in biased results (Bilotto et al. 2023; 2025). The number of samples required for robust SOC assessment with suitably low uncertainty is linked to soil variability, which can be managed through stratified sampling. This involves classifying soils into homogeneous polygons based on soil types and/or field practices, enhancing representativeness and precision (Carter & Gregorich, 2006). To ascertain SOC variability in the topsoil (0-30 cm), composite sampling from defined homogeneous strata is recommended. This method reduces variability within the study area and ensures statistical reliability (Carter & Gregorich, 2006). Additionally, using remote sensing technologies and gaining a deeper understanding of soil processes can enable flexible and reliable modeling approaches. Combining these methods brings together the spatial accuracy of geostatistics, the explanatory power of environmental correlation models, and the predictive reliability of hybrid models (Heuvelink & Webster, 2001). Although increasing the number of samples typically improves precision, logistical and economic factors must be taken into consideration. Consequently, sampling guidelines recommend collecting 15-30 composite samples per homogeneous management unit to reliably capture SOC variability (FAO-WRB, 2015).

Bulgarian soils are diverse due to varied topography and the position of the nation between temperate continental and Mediterranean climate zones (Penin, 2007). This results in pronounced regional differences in temperature and precipitation. The northern Danubian Plain, Bulgaria’s main agricultural region, is characterized by fertile Chernozems and Phaeozems on loess soils in contrast, the south features Chromic Luvisols and Vertisols (Smolnitza). Agricultural soils in Bulgaria have been subjected to intensive farming practices, with limited data available on SOC status and its spatial variability. Koutev and Kolev (2009) reported that SOC has declined significantly in Bulgarian agricultural soils due to prolonged cultivation. Initial humus levels of 3-5% have declined to contemporary values of 1-3% in many arable Chernozems. Even so, European studies indicate that Bulgarian soils, particularly the Chernozems and Kastanozem, can be very productive. However,

they differ significantly in their capacity to store SOC (Jones et al., 2005). This points to the urgent need for national evaluations to ensure the sustainable management of soil resources.
Given these challenges, coordinated holistic geospatial assessments are essential for identifying vulnerable regions and applying targeted management strategies. This study offers a detailed spatial analysis of SOC in major grain producing areas of Bulgaria, using remote sensing and physical soil samples. This approach creates a basic dataset for developing future soil conservation policies and achieving the goals of sustainable development. The objective of this paper was to enumerate the mean and variability of SOC levels in Bulgarian agricultural soils. The method aims to lay the groundwork for a deeper understanding of the dynamics of soil SOC, considering the diversity of soil types and geographical areas across the country.

MATERIALS AND METHODS

The study area transversed all agricultural land in Bulgaria, particularly major grain producing regions. The study sites include plots primarily used for cultivating crops such as sunflowers, wheat, corn and barley. It is important to note that these lands have historically undergone intensive cultivation practices characterized by heavy tillage. The sampling strategy incorporated pre-sampling stratification based on the FAO World Reference Base (FAO-WRB) for Soil Resources, an internationally recognized system that classifies soils according to their genesis, horizons and properties (FAO-WRB, 2015). To achieve robust representation of SOC variability, farm fields involved in grain production were stratified into homogeneous soil polygons, reflecting typical variability within Bulgarian agricultural landscapes. Stratification was considered in terms of soil type and texture to define distinct sampling zones with an area of approximately 7,000 ha. This method allowed a robust and scientifically valid representation of the regional soil diversity for subsequent analyses. Prior to sampling, comprehensive farm and geospatial data were standardized into shapefile (.shp) format using ArcGIS. Each field is represented as a vector polygon on a map. The entire area containing all fields was stratified based on the national soil survey data from authoritative sources. For comprehensive methods pertaining to this national soil stratification project, please refer to the work of Koynov et al. (1968). The FAO-WRB classification system was subsequently incorporated into the map, which has been digitized and made publicly available. A standard soil sampling protocol (in accordance with ISO 18400-205:2018) was then implemented to ensure spatial representativeness and analytical reliability. Within each stratum, a random sampling design was applied. Each composite soil sample was formed by systematically collecting 15 sub-samples around a predefined centroid within a circular area approximately 100 meters in diameter. Sampling was performed at a consistent depth of 0-30 cm using an automated Wintex 1000 sampler, extracting uniform soil cores. Approximately 0.5 kg composite samples were labeled with barcodes, geo-referenced (see Figure 1), digitally documented, and transported to the laboratory. A total of 1,287 composite soil samples were collected in January–March 2023.

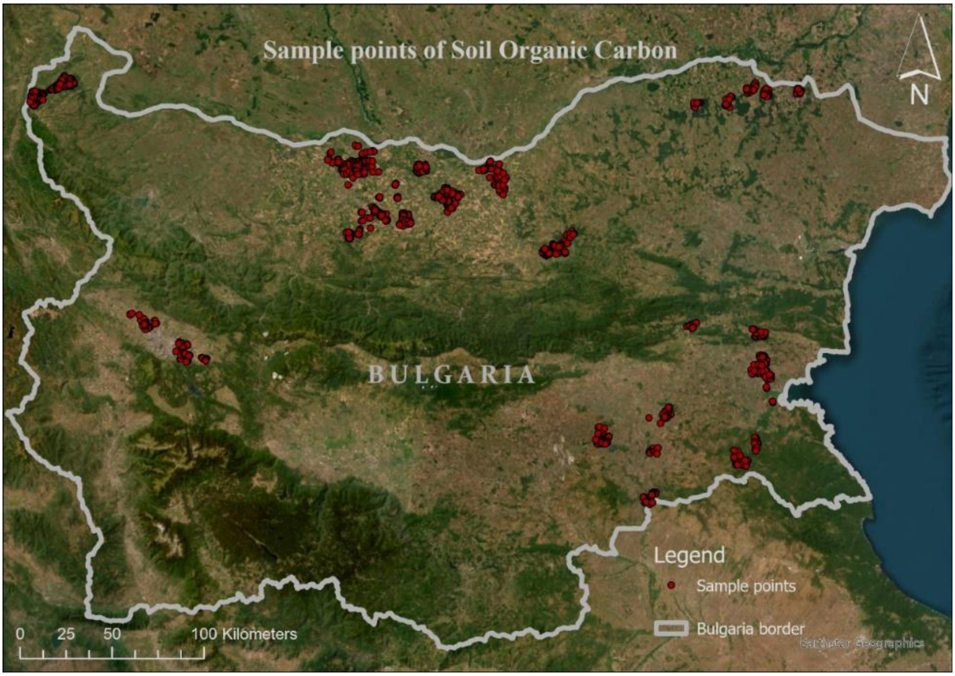

Figure 1. Sample locations for the study represented by red dots.

The laboratory procedure involved air-drying and sieving the samples to a size of <2 mm. The organic carbon content was analyzed through dry combustion (ISO 10694) using an elemental analyzer (Elementar vario MAX cube). As part of this, oxidizing carbon was detected at temperatures between 900-1000°C, with subsequent carbon dioxide detection via thermal conductivity. Maintaining data integrity was achieved through the implementation of rigorous laboratory quality control procedures. These procedures included barcode-based sample tracking and fully documented analytical protocols. Pre-processing was conducted to analyze the distribution and extent of the dataset. Next, spatial analysis was performed in a Geographic Information System (GIS) environment was done, using a feature binning approach in ArcGIS Pro. This method involves aggregating individual data points, grouping them into 'bins', and calculating the average value for each bin.

RESULTS AND DISCUSSION

The comprehensive statistical and spatial analysis of 1,287 composite soil samples from grain-producing regions in Bulgaria revealed significant variability in SOC content, with value ranging between 0.8% and 4.4%. The mean was 1.9% with a standard deviation of 0.4% (Table 1). These values exhibit moderate spatial heterogeneity due to the diversity of soil types sampled, land-use practices, and regional climatic conditions.

Table 1. Soil organic carbon concentration (%) summary statistics

Sample count	Mean	Standard deviation	Min	Q1 (25%)	Median	Q3 (75%)	Max
1287	1.90	0.44	0.82	1.60	1.86	2.15	4.41

The analysis revealed notable variation in SOC content among FAO-WRB soil classifications. The soils sampled most frequently included Calcari-haplic Kastanozems (n = 250), Haplic Chernozems (n = 135), Eutric Vertisols (n = 94), Dystric Fluvisols (n = 88) and Verti-gleic Chernozems (n = 86). Calcari-haplic Kastanozems displayed moderate SOC levels. Regions with these soils suggest intensive cultivation with limited organic amendments, which could potentially cause soil degradation. Notably, Albic Luvisols had lower mean SOC values (1.61% ± 0.45), which is indicative of their potential susceptibility to degradation due to intensive cultivation and low organic matter input. By contrast, Chromic Luvisols (1.77% ± 0.39) and Dystric Fluvisols (1.77% ± 0.38) exhibited higher SOC content, which suggests improved soil condition. This could be due to higher moisture availability and organic matter accumulation. Spatial analysis using georeferenced sampling points revealed clusters of soils with extreme SOC values (Figure 2).

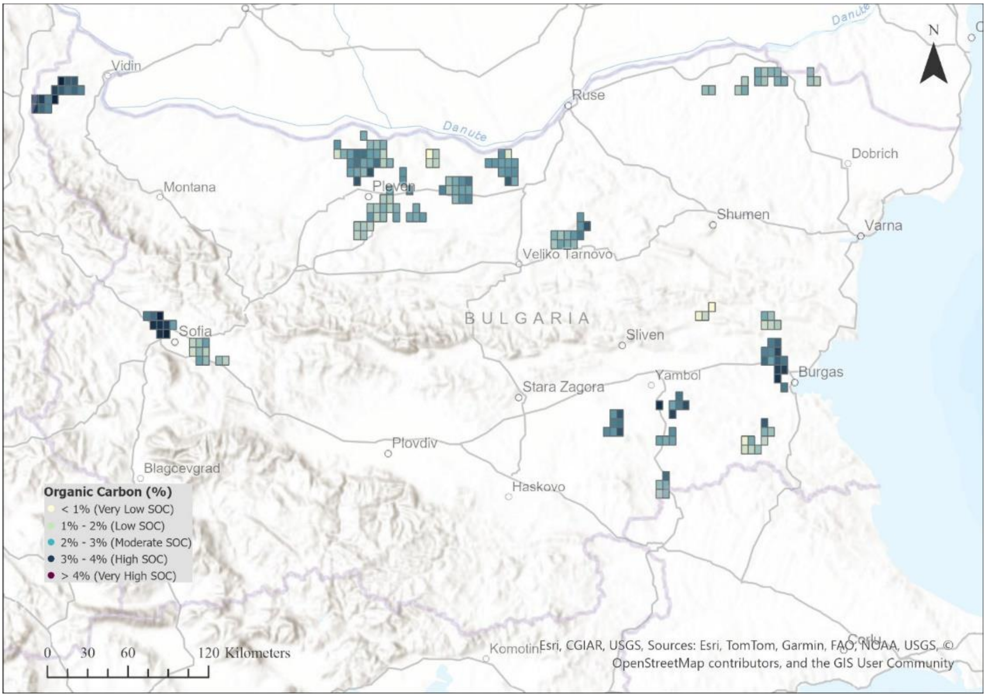

Figure 2. Spatial distribution of soil organic carbon concentrations in Bulgarian agricultural land.

Soils with the lowest carbon content were found in the southeastern regions, with the lowest values observed in the municipalities of Kirovo (0.82%), Golyamo Bukovo (0.87%) and Lozitsa (0.91%). These areas are likely to be more vulnerable to erosion and degradation, requiring the urgent implementation of sustainable agricultural practices. In contrast, the highest SOC values were recorded in northwestern Bulgaria, particularly in the municipalities of Tsar Petrovo (4.41%) and Kula (4.26%). These results imply either the presence of richer soils or more effective historical management practices that promote higher organic carbon sequestration.

In concert with the spatial insights of this study, the EU analysis of Tóth et al. (2016) provides valuable context for interpreting SOC patterns in Bulgaria. Their harmonized mapping, based on the LUCAS dataset, confirms that Bulgarian agricultural soils, especially in the Danubian Plain, fall within the lower to moderate SOC range at the European level. These findings are consistent with our identification of carbon-depleted regions that are intensively cultivated and located in warm and dry climes. While Tóth et al. provide broad-scale benchmarks, our study contributes finer-resolution SOC measurements reflecting current land use and management. This work fills a key data gap and lays the groundwork for future national assessments aimed at improving SOC monitoring and guiding climate-smart agricultural practices.

The findings of Hristov and Filcheva (2017) also support our spatial analysis, emphasizing the significant impact of pedoclimatic regimes on SOC accumulation. Their results reveal elevated SOC stocks of up to 255 t C ha^{-1} in cool moist zones, which correspond with fulvic-dominated humus profiles. Conversely, warmer, drier areas are characterized by lower SOC and humic-type humus, reflecting patterns in our study across southeastern Bulgaria. Together, these insights emphasize integrated influences of climate and land management on SOC dynamics, supporting the implementation of targeted mitigation strategies such as reduced or no-till farming and adoption of organic amendments in areas with depleted soil carbon.

Although the present study is one of the most extensive studies of SOC in Bulgarian agriculture to date, several limitations must be acknowledged. The single-season snapshot (2023) restricts the scope for temporal interpretation, and the exclusive focus on the 0-30 cm layer means that deeper SOC pools are not detected. Methodological uncertainties and lack of representation of certain factors provide a valuable baseline for future monitoring and highlight areas where national soil carbon monitoring process could be improved. The moderate spatial variability of SOC highlights the importance of contextualized soil management strategies. Low-SOC zones, which can be identified using geospatial techniques, should be prioritized for sustainable interventions such as reduced tillage, cover cropping, residue retention and use of organic amendments, as these practices are known to enhance sequestration and resilience. Conversely, high-SOC areas could serve as benchmarks for best practice and thus quantification of SOC improvement potential (‘SOC gaps’). The large sample size of the study and its stratified sampling design ensure rigour in documenting these patterns, providing a critical foundation for evidence-based agricultural policy and future monitoring efforts.

CONCLUSION

Through analysis of 1,287 composite soil samples from grain-production regions in Bulgaria, we revealed significant variability in SOC, ranging from 0.8% to 4.4%, with a mean of 1.9%. Albic Luvisols had lower SOC levels compared with Chromic Luvisols and Dystric Fluvisols. The analysis identified clusters with extreme SOC values, with the lowest SOC in southeastern Bulgaria (e.g., municipalities of Kirovo, Golyamo Bukovo, and Lozitsa) and the highest in northwestern Bulgaria (e.g., Tsar Petrovo and Kula), reflecting regional differences in management and environmental conditions. The data demonstrated the significant influence of climatic conditions and agricultural practices on SOC accumulation. Based on the extensive sample size, this study provides a solid foundation for developing management policies that could be invoked to improve soil resilience in Bulgaria. Future efforts should focus on long-term monitoring and integrating geospatial technologies for more precise land management.

ACKNOWLEDGEMENTS

This research was made possible thanks to the soil data provided by the “AgroVar Carbon Program”.

REFERENCES

Bilotto, F., Christie-Whitehead, K. M., Malcolm, B., & Harrison, M. T. (2023). Carbon, cash, cattle and the climate crisis. Sustainability Science, 18(4), 1795–1811.

Bilotto, F., Christie-Whitehead, K. M., Malcolm, B., Barnes, N., Cullen, B., Ayre, M., & Harrison, M. T. (2025). Costs of transitioning the livestock sector to net-zero emissions under future climates. Nature Communications, 16(1), 3810.

Carter, M. R., & Gregorich, E. G. (Eds.). (2006). Soil Sampling and Methods of Analysis (2nd ed.). CRC Press.

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on SOC stocks—a meta-analysis. Global Change Biology, 17(4), 1658–1670.

Heuvelink, G. B. M., & Webster, R. (2001). Modelling soil variation: Past, present, and future. Geoderma, 100(3–4), 269–301.

Henry, B., Dalal, R., Harrison, M. T., & Keating, B. (2022). In C. Rumpel (Ed.), Understanding and Fostering Soil Carbon Sequestration. Burleigh Dodds.

Hristov, B., & Filcheva, E. (2017). Soil organic matter in different pedoclimatic zones of Bulgaria. Eurasian Journal of Soil Science, 6, 65–74.

IUSS Working Group WRB. (2015). World Reference Base for Soil Resources 2014, update 2015. FAO, Rome.

Jones, R. J. A., Hiederer, R., Rusco, E., & Montanarella, L. (2005). Estimating organic carbon in European soils. European Journal of Soil Science, 56, 655–671.

Kabir, M. J., Alam, K., Mushtaq, S., Bilotto, F., Christie-Whitehead, K. M., & Harrison, M. T. (2024). Extreme weather dominates farm management effects on long-term soil carbon. Trends in Food Science & Technology, 146, 104409.

Koutev, V., & Kolev, N. (2009). Management of Bulgarian soil resources fertility. Bulg. J. Ecol. Sci., 8.

Koynov, V., et al. (1968). Soil Map of Bulgaria, Scale 1:400,000. Sofia. (Digitized 2000 by D. Zhivkov).

McDonald, S. E., Badgery, W., Clarendon, S., Orgill, S., Sinclair, K., et al. (2023). Grazing management for soil carbon in Australia: A review. Journal of Environmental Management, 347, 119146.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., et al. (2015). New assessment of soil loss by water erosion in Europe. Environmental Science & Policy, 54, 438–447.

Penin, R. L. (2007). Natural Geography of Bulgaria. Sofia: Bulvest 2000.

Rumpel, C., Amiraslani, F., Koutika, L. S., Smith, P., et al. (2018). Put more carbon in soils to meet Paris climate pledges. Nature, 564(7734), 32–34.

Six, J., Conant, R. T., Paul, E. A., et al. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation. Plant and Soil, 241, 155–176.

Tóth, G., Antofie, T., Jones, A., & Apostol, B. (2016). The LUCAS 2012 topsoil survey of Bulgaria and Romania. Environmental Engineering and Management Journal, 15, 2651–2662.

Van Hoof, S. (2023). Climate change mitigation in agriculture: Barriers to carbon farming policies in the EU. Sustainability, 15(13), 10452.