Communications in Soil Science and Plant Analysis

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/lcss20

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To cite this article: Cristina I. Dias Rodrigues, Luís Miguel Brito & Leonel J. R. Nunes (2025) Dynamics of Soil Carbon Average Content at Different Depths: Insights from a Global Approach to Climate Change Mitigation, Communications in Soil Science and Plant Analysis, 56:6, 911-925, DOI: 10.1080/00103624.2024.2439292

To link to this article: https://doi.org/10.1080/00103624.2024.2439292

COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS
2025, VOL. 56, NO. 6, 911–925
https://doi.org/10.1080/00103624.2024.2439292

Dynamics of Soil Carbon Average Content at Different Depths: Insights from a Global Approach to Climate Change Mitigation

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ABSTRACT

This study provides an in-depth examination of the average values of gravimetric carbon content, measured in grams per kilogram (g/kg), and the organic Carbon (OC) content, quantified in kilograms per square meter (kg/m^2), within various soil classifications and depths. Highlighting the relevance of such research, it delves into the intricacies of soil OC dynamics across diverse depth strata and offers a comparative analysis of different soil types, each with distinct carbon sequestration capacities. Utilizing the latest version of the world soil database, the research integrates three interconnected data sets: soil classification, density, and OC. In total, the study includes 51,507 soil profile layers to calculate the average gravimetric OC content in the fine-earth fraction. In parallel, the average OC content in the fine-earth fraction was determined across 6,197 soil profile layers. This comprehensive data is organized into 34 separate soil units, each dissected across four depth categories: 0–30 cm, 0–100 cm, 0–200 cm and 0–2590 cm. The findings from this analysis reveal a consistent pattern: as depth increases, both the gravimetric content and average OC content tend to decrease. However, it is noteworthy that this trend is not universal. Certain soil units demonstrate an opposing behavior, with an increase in average OC content observed at greater depths, contradicting the prevailing trend. This divergence underscores the complexity of soil OC dynamics and the inherent variability across different soil units.

ARTICLE HISTORY
Received 2 January 2024
Accepted 2 December 2024

KEYWORDS
Carbon sequestration capacity; gravimetric carbon content; organic carbon (OC) content; soil carbon dynamics; soil typologies

Introduction

On a temporal scale of decades and centuries, the main natural sinks for carbon dioxide (CO_2) consist of absorption by the oceans, plants, and soils (Soeder 2021). Considering that more than two-thirds of terrestrial carbon reserves are found in soils, which represent the largest terrestrial carbon reservoir including soil organic carbon (about 1526 PgC) and inorganic soil carbon (about 940 PgC) (Lal et al. 2021; Nieder and Benbi 2008). Soils have the capacity to store carbon for long periods, and significant changes in carbon reservoirs could significantly alter atmospheric CO_2 concentrations (Moomaw, Law, and Goetz 2020). Furthermore, maintaining appropriate carbon levels in these reservoirs is essential for reducing the risks of erosion and degradation, retaining water and nutrients, and improving soil structure (Rodrigo-Comino et al. 2020).

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Given the importance of soil carbon and its potential to become a sink for atmospheric CO_2, there has been extensive discussion in the scientific literature regarding the potential consequences of climate change on soil processes (Salimi, Almuktar, and Scholz 2021). This concern is accompanied by a desire to develop methods to enhance carbon sequestration, stimulate experimental research, and develop models and theories (Caineng et al. 2023). There is no doubt that this topic deserves special attention in today's era of climate change (Driga and Drigas 2019). While soil carbon sequestration is potentially finite, not permanent, and challenging to quantify and verify in the long term, it may serve as a risky strategy for minimizing climate effects compared to direct emission reductions (Sykes et al. 2020). However, in the short term, it can be crucial for reducing atmospheric CO_2 concentrations (Lan et al. 2021).

In recent years, there has been an increased need for accurate information on soil CO_2 concentrations at global, European, national, or regional levels due to the importance of carbon reserves for sustainable use of natural resources (Wang et al. 2021). In addition to the current concern about environmental issues such as soil degradation and contamination, information about soil carbon reserves is necessary for assessing the potential of soils to sequester CO_2 (Koutika 2022). The Kyoto Protocol and the United Nations Framework Convention on Climate Change require national inventory reports on carbon reserves, which needs precise and reliable estimates of current carbon reserves (Bossio et al. 2020).

In this context, carbon inventories and the analysis of OC distribution are essential tools for modeling the effects of various factors involved in soil carbon sequestration potential (Hughes et al. 2023). It is worth mentioning that there is a consensus regarding the relationship between soil type and carbon storage at multiple scales and under different climatic conditions (Guenet et al. 2021). During pedogenesis, weathering chemical reactions lead to changes in soil mineralogy composition, which strongly influence mineral surface area reactivity and carbon storage (Kögel-Knabner and Amelung 2021). The resulting characteristics are categorically described by soil types. In contrast to climate, vegetation, and parent material, which can serve as indicators for carbon storage at larger scales, carbon reserves can be stratified according to soil type even at smaller scales (local to sub-regional) (Qu et al. 2020). Many studies reveal a predominant influence of soil type on soil carbon reservoirs, both at the surface and subsurface (Dai et al. 2022; Elbasiouny et al. 2022; Shi et al. 2020). The link between SOC and broader environmental issues such as biodiversity loss and climate-smart agriculture is undeniable. SOC plays a crucial role in maintaining soil structure, enhancing water retention, and reducing erosion, all of which contribute to ecosystem stability. Furthermore, practices like climate-smart agriculture, which aim to reduce greenhouse gas emissions while increasing productivity, are heavily dependent on maintaining SOC levels. SOC management practices, such as composting, cover crops, and minimal soil disturbance, directly support climate mitigation by enhancing the soil's ability to sequester carbon.

Soil type is not an independent controlling factor but integrates a set of factors such as climate, parent material, and topography, which are related to properties directly affecting soil's potential to store carbon, particularly soil moisture regime and texture (Rodríguez Hernández et al. 2020). If information regarding soil properties, such as texture and moisture, is not available, soil type can serve as a suitable indicator for soil carbon storage, integrating a wide range of decisive factors (Wiesmeier et al. 2019). This research article embarks on an in-depth investigation with the aim of calculating and analyzing the average gravimetric carbon content and soil CO_2 concentration across a variety of soil types and depths. The principal objectives are to unpack the complexities of carbon storage in soils and to further comprehend their role as carbon sinks. This study is particularly pertinent within the context of climate change and the global imperative to devise effective mitigation strategies. The findings from this research are expected to yield significant insights into the domain of soil carbon sequestration, offering a robust foundation for devising sustainable management and utilization of natural resources. Moreover, the study emphasizes the importance of soil as a key regulator of carbon, thereby underlining the need to consider this vital role in the development of future environmental policies and practices.

Materials and methods

Framework

Data, information, and knowledge about soil resources at a global level are currently fragmented and even at risk of being lost or forgotten due to the costs involved in maintaining and archiving analog soil data based on paper and the physical deterioration or disintegration of such data. However, procedures have been developed to preserve, assess quality, standardize, and subsequently provide consistent global soil data to the international community, as developed within the framework of the World Soil Information Service – WoSIS – project since the release of the first dataset in 2016 (https://www.isric.org/explore/wosis, accessed on June 19, 2023). Figure 1 presents the distribution of the main soil types at a global scale, produced from information obtained from the FAO SOILS PORTAL (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/other-global-soil-maps-and-databases/en/, accessed on June 19, 2023).

The analysis conducted here was based on the latest update of the world soil database, WoSIS, from 2019, which provides standardized and quality soil profile data to support digital soil mapping and large-scale environmental applications. Since the soil profile data were provided by various entities, WoSIS considered the data quality measures, standardization of soil property definitions, soil property values (and units of measurement), and descriptions of soil analytical methods.

Currently, this database compiles several chemical soil properties, including organic carbon, total carbon, equivalent total carbonate, total nitrogen, phosphorus (extractable P, total P, and P retention), soil pH, cation exchange capacity, and electrical conductivity. Additionally, this database compiles various physical soil properties grouped according to analytically comparable procedures (aggregates),

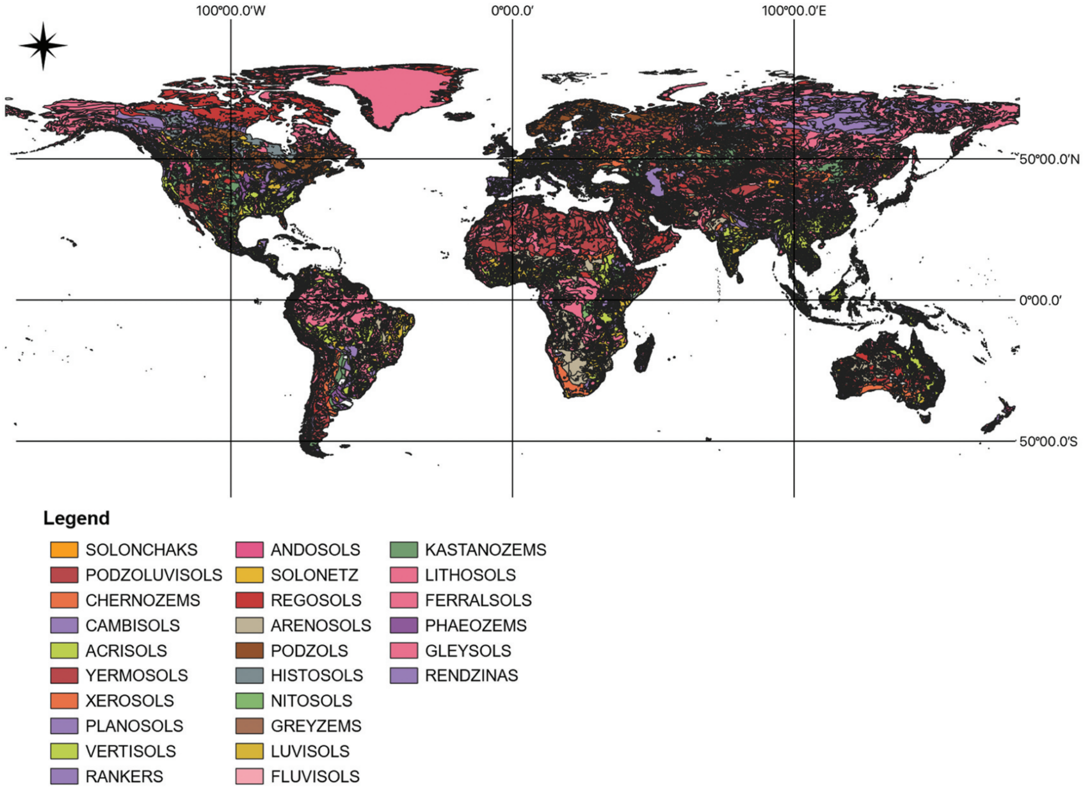

Figure 1. World soil type distribution (adapted from FAO SOILS PORTAL, https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/other-global-soil-maps-and-databases/en/, accessed on June 19, 2023).

such as soil texture (sand, silt, and clay), bulk density, coarse fragments, and water retention. At the geographical level, measures of the geographical accuracy of point data are shown, as well as an initial approximation of the uncertainty associated with operationally defined analytical methods, for possible digital soil mapping and subsequent Earth system modeling.

The standardized datasets derived from the WoSIS database are distributed in two ways. The latest version used in this analysis, WoSIS Latest, consists of over 202,000 georeferenced profiles originating from 6 continents and 177 countries. The data is available on the ISRIC – World Soil Information website for visualization and download, accessed through the Web Feature Service (WFS) by adding the link (http://maps.isric.org/mapserv?map=/map/wosis_latest.map, accessed on June 19, 2023) to a GIS application, which allows for reading and modifying data in vector format.

Data bases

Soil classification

For each soil profile, its original classification according to FAO is provided, and the corresponding version is presented if specified in the original databases. Within the WoSIS latest database, we have identified 21,714 soil profiles that include soil unit classification. Table 1 below displays the 34 soil units sorted by the number of soil profiles associated with each unit.

The data provided in Table 1 shows that the soil units vary considerably in terms of their profile numbers, which can influence the characteristics of each soil unit, including nutrient availability, water-holding capacity, and carbon sequestration potential. Among all the soil units, Luvisol presents the highest number of profiles with a total of 2,758. This significant number suggests the widespread presence of this soil type, which is known for its clay-enriched subsoil and high fertility. Close behind is Cambisol with 2,584 soil profiles, another soil type known for its potential fertility and versatility, supporting a wide range of vegetation types. Regosol and Vertisol also exhibit a high number of soil profiles, with 1,578 and 1,744 profiles respectively. Regosols are typically young soils with minimal horizon development, indicating recent soil-forming processes, while Vertisols are characterized by a high proportion of expansive clay minerals, leading to unique shrinking and swelling behaviors. At the lower end of the scale, Plinthosol, Gypsisol, and Ranker have the fewest soil profiles, with 15, 42, and 41 respectively. These soils tend to occur in more specific or harsh environmental conditions, such as waterlogged (Plinthosol), gypsum-rich (Gypsisol), or rocky areas (Ranker). The distribution of soil profiles among the other units is more evenly spread, with soil profiles ranging from a few hundred to over a thousand in units like Acrisol, Arenosol, Ferralsol, Gleysol, and Phaeozem.

Table 1. Number of profiles per soil unit.

Soil units	Soil profiles	Soil units	Soil profiles
Acrisol	1228	Lixisol	373
Alisol	290	Luvisol	2758
Andosol	344	Nitisol	138
Anthrosol	214	Nitosol	167
Arenosol	1332	Phaeozem	1185
Calcisol	510	Planosol	298
Cambisol	2584	Plinthosol	15
Chernozem	532	Podzol	274
Ferralsol	802	Podzoluvisol	282
Fluvisol	942	Ranker	41
Gleysol	968	Regosol	1578
Greyzem	69	Rendzina	455
Gypsisol	42	Solonchak	354
Histosol	208	Solonetz	318
Kastanozem	270	Vertisol	1744
Leptosol	421	Xerosol	572
Lithosol	102	Yermosol	304

Density

The research data set includes a substantial volume of information pertaining to the bulk density of the fine-earth fraction in the soil, which has been ascertained using oven-dried methods and is measured in kilograms per cubic decimeter (kg/dm3). The determination of bulk density is crucial, as it provides insight into soil structure and porosity, key factors that influence the movement of air and water in the soil, root penetration, and overall soil productivity. Each soil profile in the dataset, along with each specific layer within the soil profile, is represented with this density data. The depth-based resolution of the data underscores the heterogeneity of soil characteristics, reflecting how properties can vary significantly from the surface to deeper layers. The comprehensive nature of this data provides an opportunity for in-depth study of soil properties at varying depths, critical for understanding complex soil processes. The dataset consists of an impressive total of 123,585 data points, dispersed across 24,571 individual soil profiles. These numerous data points represent a broad spectrum of soil layers across the profiles, amplifying the dataset's value for soil-related studies. The extensive and granular nature of this data provides a robust basis for diverse analyses, from local soil management strategies to large-scale, climate-related soil research.

Organic carbon

The WoSIS Latest database, a rich resource of soil information, includes an extensive collection of data points pertaining to the gravimetric organic carbon content in the fine-earth fraction, expressed in grams per kilogram (g/kg). This parameter is of paramount importance, as it offers crucial insights into soil health, fertility, and carbon sequestration capacity, factors that are instrumental in shaping the ecological balance and agricultural productivity of a region. This substantial collection of data encompasses a staggering total of 458,406 individual data points. These data points, gathered meticulously from across the globe, are distributed among 121,509 distinct soil profiles, each profile presenting a unique snapshot of the soil's characteristics at a specific site. The recorded data points are carefully determined at a range of different soil depths, providing an in-depth, multi-layered understanding of the distribution and concentration of organic carbon within the soil strata. The depth measurements are presented as intervals, marking the upper and lower limits of the soil layer where the readings were taken. These depth intervals span from the surface level, marked as 0 centimeters, to a remarkable depth of 2,590 centimeters. This extensive depth range underscores the comprehensive nature of the database, capturing the complexity and diversity of global soil profiles.

Data analysis

The data processing began using the QGIS application, which allowed for the identification, selection, and display of attribute tables. This involved collecting and processing information from three distinct layers: ms:wosis_latest_profiles, ms:wosis_latest_bdfiod, and ms:wosis_latest_orgc. The first layer, ms:wosis_latest_profiles, provides information related to soil profile identification, such as the soil profile ID number, continent, country, and soil classification according to FAO. The second layer, ms:wosis_latest_bdfiod, provides information on the bulk density of the fine-earth fraction when dried in an oven, based on soil profile identification and layer identification. The third layer, ms:wosis_latest_orgc, provides information on the gravimetric carbon content in the fine-earth fraction. It includes the soil profile ID number, layer identification, country, upper layer depth (in cm), lower layer depth (in cm), and gravimetric carbon content (in g/kg).

After consulting the respective attribute tables, the data was extracted and saved as an Excel file for further processing. Initially, the data from the three layers were analyzed, revealing that the soil profile identification data was present in all three attribute tables. This allowed for correlating the soil classification with the table containing information on the gravimetric carbon content in the fine-earth fraction, based on depth. The data related to layer identification, however, appeared in only two out of the three attribute tables: ms:wosis_latest_bdfiod and ms:wosis_latest_orgc. This allowed for correlating the bulk density of the fine-earth fraction with the gravimetric carbon content at different depths.

To obtain the data on the average carbon content in the fine-earth fraction per depth in kg/m^2, the gravimetric carbon content (g/kg), bulk density of the fine-earth fraction (kg/dm^3), and sample depth (cm) were multiplied together. Consequently, a single database was created, containing information on soil classification (according to FAO), bulk density of the fine-earth fraction (kg/dm^3), gravimetric carbon content in the fine-earth fraction per depth (g/kg), and average carbon content in the fine-earth fraction per depth (kg/m^2). Subsequently, using Excel's PivotTable tool, the data was simplified and summarized. The upper depths were grouped into intervals of 0–30 cm, 0–100 cm, 0–200 cm, and 0–2590 cm, and the respective averages were calculated per soil unit for the gravimetric carbon content in the fine-earth fraction per depth (g/kg) and the average carbon content in the fine-earth fraction per depth (kg/m^2).

Results

Gravimetric OC content in the fine-earth fraction

The results concerning the gravimetric content of organic carbon (OC) in the fine-earth fraction, in g/kg, shown in Table 2, were calculated based on the averages of 51,507 soil profile layers categorized

Table 2. Gravimetric organic carbon content in the fine-earth fraction by depth and soil unit.

	Gravimetric organic carbon content in the fine earth fraction by depth (g/kg)			
Soil classification	0–30 cm	0–100 cm	0–200 cm	0–2590 cm
Acrisol	16.25	10.73	9.32	9.14
Alisol	17.85	10.13	8.25	8.25
Andosol	64.58	44.18	38.46	38.24
Anthrosol	13.21	9.97	9.58	9.55
Arenosol	5.41	3.80	3.27	3.25
Calcisol	9.53	7.16	6.02	6.02
Cambisol	22.00	14.12	12.15	12.14
Chernozem	21.75	14.43	11.52	11.45
Ferralsol	19.89	13.83	11.64	11.32
Fluvisol	16.63	12.25	11.57	11.56
Gleysol	43.37	24.67	21.86	21.80
Greyzem	43.07	24.38	19.67	19.24
Gypsisol	2.94	2.45	2.51	2.51
Histosol	315.80	326.54	310.83	312.22
Kastanozem	15.91	11.75	9.96	9.90
Leptosol	38.94	29.11	28.10	28.10
Lithosol	28.72	23.15	21.58	21.58
Lixisol	11.69	8.67	7.67	7.85
Luvisol	14.19	9.34	8.17	8.14
Nitisol	22.57	17.31	14.80	14.53
Nitosol	18.27	12.85	10.10	9.75
Phaeozem	22.24	14.68	12.52	12.44
Planosol	17.77	9.80	8.69	8.67
Plinthosol	9.21	6.51	6.13	6.13
Podzol	89.41	51.35	46.68	46.52
Podzoluvisol	54.32	25.98	22.23	21.85
Ranker	77.79	69.23	69.23	69.23
Regosol	14.13	9.77	8.83	8.79
Rendzina	36.20	31.83	31.56	31.56
Solonchak	9.93	7.17	6.89	6.86
Solonetz	11.31	7.39	6.52	6.51
Vertisol	17.29	11.81	9.76	9.70
Xerosol	8.55	6.44	5.86	5.86
Yermosol	3.16	2.57	2.37	2.37
Average content	33.35	26.04	23.95	23.91

into 34 soil units, distributed by depths, namely, 0–30 cm, 0–100 cm, 0–200 cm, and 0–250 cm. The attained results revealed that 22 out of the 34 soil units exhibit a decreasing trend in gravimetric content of OC in the fine-earth fraction as depth increases. These units include Acrisol, Andosol, Anthrosol, Arenosol, Cambisol, Chernozem, Ferralsol, Fluvisol, Gleysol, Greyzem, Kastanozem, Luvisol, Nitisol, Nitosol, Phaeozem, Planosol, Podzol, Podzoluvisol, Regosol, Solonchak, Solonetz, and Vertisol. The results also showed that 9 out of the 34 soil units demonstrate a decreasing trend in gravimetric content of OC in the fine-earth fraction up to a depth of 0–200 cm, while either remaining constant or showing slight increase beyond that depth. These units include Alisol, Calcisol, Leptosol, Lithosol, Lixisol, Plinthosol, Rendzina, Xerosol, and Yermosol. Additionally, the obtained results revealed that 2 out of the 34 soil units display a decreasing trend in gravimetric content of OC in the fine-earth fraction up to a depth of 0–100 cm, while either remaining constant or showing slight increase below that depth. These units are Gypsisol and Ranker. Furthermore, it was observed that only 1 out of the 34 soil units exhibits an increasing trend in gravimetric content of OC in the fine-earth fraction up to a depth of 0–100 cm, followed by a decrease beyond 0–100 cm and a slight increase after 0–200 cm. This unit is known as Histosol. It is worth mentioning that Histosol represents the soil type with the highest gravimetric content of OC in the fine-earth fraction at all depths, recording values exceeding 300 g/kg of OC. Regarding the soil units with the lowest gravimetric content of OC in the fine-earth fraction (below 10 g/kg of OC) at all depths, these include Arenosol, Calcisol, Gypsisol, Plinthosol, Solonchak, Xerosol, and Yermosol.

Table 2 provides an overview of the gravimetric organic carbon content in the fine-earth fraction for various soil classifications at different depths. Notably, the values of organic carbon content vary widely between different soil types, indicating the diverse capacities of these soils to sequester carbon. For the depth of 0–30 cm, Andosol demonstrates the highest organic carbon content (64.58 g/kg), followed by Histosol (315.80 g/kg), which dramatically increases with depth, reaching 326.54 g/kg at the 0–100 cm depth. The most carbon-rich soil, Histosol, is typically associated with wetland environments and contains a high proportion of organic matter. This remarkably high value is an anomaly when compared with the rest of the soil units, and it appears to reflect Histosol's unique capacity to sequester organic carbon. On the other end of the spectrum, Gypsisol and Yermosol display the lowest organic carbon content across all depth intervals. Given their arid or semi-arid environments, these soil types often exhibit low organic content due to less vegetation and more rapid organic matter decomposition. Most soil types, including Acrisol, Alisol, Anthrosol, and Cambisol, among others, show a gradual decrease in organic carbon content as depth increases, which aligns with the common understanding that organic matter, and hence organic carbon, is concentrated more in the upper soil layers. This is attributed to organic matter being mostly derived from plant residues, which are more abundantly present on and near the soil surface. However, certain soil types such as Ranker, Rendzina, Leptosol, and Lithosol show relatively stable organic carbon content across different depths. This could be attributed to their specific properties and the environments in which they are typically found. In general, the average organic carbon content across all soil types declines with increasing soil depth from 33.35 g/kg at 0–30 cm to 23.91 g/kg at 0–2590 cm. These figures suggest a general trend of decreasing organic carbon concentration with soil depth, which is consistent with existing knowledge in soil science.

To test the statistical significance of differences in gravimetric organic carbon content among the different soil units and depths presented in Table 2 the application of Analysis of Variance (ANOVA) is suggested as the best option. ANOVA is particularly suitable for these data, given it allows for comparison of the means of more than two groups (in this case, soil units and depth ranges) and determines whether the differences between the groups are statistically significant. After applying the ANOVA test, it was found that the differences in the mean gravimetric organic carbon content for the different soil units and depths are statistically significant ($p < .05$). This outcome implies that soil type and depth are indeed critical factors in determining the concentration of organic carbon in the soil. The variation in the organic carbon content among different soil types is likely attributable to inherent differences in their physical and chemical properties, as well as the climatic and biological conditions they experience. However, this statistical significance does not reveal the specific soil types or depths where the differences lie, so a post-hoc test like the Tukey HSD (Honest Significant Difference) test would be necessary for pairwise comparisons. It is also crucial to consider the impact of other variables not included in this analysis, such as climate, land use, and management practices, on the organic carbon content of soils. These factors could provide further insights into the complex dynamics of soil organic carbon sequestration.

Average content of OC in the fine-earth fraction

The most commonly determined results are expressed per unit area, specifically as total kg/cm^2, t/ha, or Gt/m^2 (Pg/m^2). In this regard, using the values of density and sample collection depth, the average content of OC was calculated in kg/m^2. The results regarding the average OC content in the fine-earth fraction, in kg/m^2, presented in Table 3, were calculated based on the averages of 6197 soil profile layers, categorized into 34 soil units, distributed by depths, namely, 0–30 cm, 0–100 cm, 0–200 cm, and 0–2590 cm. The obtained results revealed that 18 out of the 34 soil units show a decreasing trend in the average OC content in the fine-earth fraction as depth increases. These units include Acrisol, Cambisol, Gleysol, and Podzoluvisol for all depths; Andosol, Gypsisol, and Xerosol, up to a depth of 0–100 cm, remaining stable or slightly increasing after this depth; Alisol, Calcisol, Chernozem, Greyzem, Kastanozem,

Table 3. Average content per surface unit of organic carbon (OC) in the fine fraction by depth and per soil unit.

	Average content of OC in the fine earth fraction by depth (kg/m^2)			
Soil units	0–30 cm	0–100 cm	0–200 cm	0–2590 cm
Acrisol	2.63	2.42	2.32	2.32
Alisol	2.96	2.24	1.91	1.91
Andosol	4.29	3.99	4.14	4.14
Anthrosol	-	-	-	-
Arenosol	1.72	1.91	1.94	1.94
Calcisol	4.03	3.61	3.16	3.16
Cambisol	3.78	3.27	3.06	3.05
Chernozem	6.52	4.98	4.10	4.11
Ferralsol	2.34	2.58	2.63	2.63
Fluvisol	3.19	3.42	3.40	3.37
Gleysol	4.48	3.88	3.75	3.75
Greyzem	4.63	3.38	3.09	3.09
Gypsisol	0.36	0.34	0.34	0.34
Histosol	14.03	19.24	19.24	19.24
Kastanozem	4.96	4.09	3.47	3.47
Leptosol	5.96	6.07	5.94	5.94
Lithosol	-	3.75	4.94	4.94
Lixisol	1.46	1.26	1.26	1.26
Luvisol	3.02	2.74	2.50	2.50
Nitisol	4.85	5.39	5.26	5.26
Nitosol	3.21	4.19	4.40	4.40
Phaeozem	5.78	4.64	4.06	4.06
Planosol	6.95	4.16	3.47	3.47
Plinthosol	1.02	1.02	1.02	1.02
Podzol	2.85	3.15	4.87	4.87
Podzoluvisol	3.37	2.35	2.27	2.25
Ranker	-	-	-	-
Regosol	4.08	3.61	3.45	3.45
Rendzina	-	-	-	-
Solonchak	3.08	2.85	2.63	2.63
Solonetz	2.85	2.91	2.68	2.68
Vertisol	4.76	4.47	3.95	3.95
Xerosol	1.82	1.46	1.55	1.55
Yermosol	-	-	-	-
Average content	3.96	3.78	3.69	3.69

Luvisol, Phaeozem, Planosol, Regosol, Solonchak, and Vertisol, up to a depth of 0–200 cm, remaining stable or slightly increasing after this depth. The average OC content in the fine-earth fraction for the Plinthosol soil unit remained constant throughout the entire depth (1.02 kg/m^2).

The results also revealed that 11 out of the 34 soil units show an increasing trend in the average OC content in the fine-earth fraction as depth increases. These units include Arenosol for all depths; Histosol, Leptosol, Lixisol, Nitisol, and Solonetz, up to a depth of 0-100 cm, remaining stable or slightly decreasing after this depth; Ferralsol, Fluvisol, Lithosol, Nitosol, and Podzol, up to a depth of 0–200 cm, remaining stable or slightly decreasing after this depth. It is worth mentioning that due to the lack of density data for 4 out of the 34 soil units, namely Anthrosol, Ranker, Rendzina, and Yermosol, it was not possible to determine the average OC content in the fine-earth fraction. Furthermore, it should be noted that Histosol represents the soil type with the highest average OC content in the fine-earth fraction at all depths, ranging from 14.03 kg/m^2 (0–30 cm) to 19.24 kg/m^2 (0–100 cm, 0–200 cm, and 0–2590 cm). Regarding the soil units with the lowest average OC content in the fine-earth fraction (below 2.00 kg/m^2) at all depths, these include Arenosol, Gypsisol, Lixisol, Plinthosol, and Xerosol.

From the analysis of the data presented in Table 3 can be seen a considerable variability in OC content across the different soil units, which range from 0.36 kg/m^2 in Gypsisols to a high of 14.03 kg/m^2 in Histosols in the top 0–30 cm of soil. This highlights the significant role that soil type can play in carbon sequestration. The depth-specific data presented also offers insights into OC distribution in the soil profile. Notably, in most soil units, there is a general trend of decreasing OC content as the depth increases from 0–30 cm to 0–2590 cm. For instance, Acrisol and Alisol both show this pattern, suggesting that the majority of OC is concentrated in the topsoil layers. This finding aligns with general expectations given that OC is typically most abundant in topsoil where organic matter decomposition is most active. However, some soil types, such as Andosols and Leptosols, display an increase or relative stability in OC content with increasing depth. This suggests that these soil units have a particular capacity for deep carbon storage. Histosols are also an outlier, showing an increase in OC content with depth, indicating an exceptional ability for carbon sequestration, likely due to their high organic matter content. Meanwhile, soil units such as Anthrosol, Ranker, Rendzina, and Yermosol lack data for OC content. This could be due to a variety of reasons such as difficulties in sampling, distinctive soil properties, or low prevalence in the sampling area, and warrants further investigation. In terms of the average content across all soil units, there is a marginal decline from 3.96 kg/m^2 at 0–30 cm depth to 3.69 kg/m^2 at 0–2590 cm depth. This suggests that, on average, the soils surveyed have the majority of their OC stored in the upper layers, affirming the significance of the topsoil in carbon storage and sequestration.

To analyze the data presented in Table 3, a repeated measures ANOVA test could be applied to assess the differences in average OC content across varying depths for different soil units. The test could evaluate whether the differences in OC content observed at varying soil depths are statistically significant, or if they occur by chance. The repeated measures ANOVA could assess the main effects of soil unit type and depth, as well as the interaction effect between the two. This will allow us to determine if the change in OC content with depth differs significantly among the various soil units. Following the statistical analysis, the data reveals considerable variability in OC content across different soil units, ranging from 0.36 kg/m^2 in Gypsisols to 14.03 kg/m^2 in Histosols within the 0–30 cm soil depth. Notably, there is an apparent trend of decreasing OC content with increasing soil depth in most soil units, but exceptions like Andosols, Leptosols, and Histosols show an increase or relative stability. This indicates these soils have unique capacities for deep carbon storage. The lack of data for units like Anthrosol, Ranker, Rendzina, and Yermosol requires further research for a comprehensive understanding of soil OC content patterns. The average content across all units shows a slight decline from 3.96 kg/m^2 at 0–30 cm depth to 3.69

kg/m^2 at 0–2590 cm depth. This finding underscores the importance of the topsoil layer in carbon storage and sequestration.

Discussion

The vertical distribution of OC in soils is a dynamic and complex process influenced by a multitude of factors, including the distribution of organic matter, decomposition rates, soil texture and structure, root distribution and activity, and human activities (Saljnikov et al. 2022). Generally, OC content tends to decrease with increasing soil depth, a pattern that is evident in our study and is broadly consistent with the global soil carbon distribution (Heckman et al. 2022). This trend can be attributed to several key factors. The primary factor is the distribution of organic matter, which is typically more concentrated in the surface layers of soil (Mtyobile, Muzangwa, and Mnkeni 2019). The surface soil, or the topsoil, receives regular inputs of organic matter in the form of dead plant material, such as leaves and roots, and animal residues (Prescott and Vesterdal 2021). As a result, the topsoil is rich in OC. As we move deeper into the soil profile, the amount of organic matter generally decreases, leading to a lower OC content (Xia et al. 2021). The rate of decomposition of organic matter also plays a critical role in determining the OC content at different depths (Zheng et al. 2021). Organic matter in the surface soil is more readily available for decomposition by soil microorganisms, which convert the OC into CO_2 that is released into the atmosphere (Witzgall et al. 2021). In contrast, organic matter in the subsoil layers is less accessible to microorganisms due to physical protection within soil aggregates or chemical stabilization by soil minerals, resulting in slower decomposition and potentially higher OC content (Kögel-Knabner and Amelung 2021). Soil texture and structure also influence the depth distribution of OC (Zhu et al. 2021). Soils with a higher clay content tend to have more OC because clay particles can physically protect organic matter from decomposition and form stable organo-mineral complexes (Soinne et al. 2021). This can lead to greater OC storage in subsoils, which often have a higher clay content than topsoils (Antony et al. 2022). In fact, the presence of hardpans, claypans, or bedrock can limit the downward movement of organic matter and OC in the soil profile (Avornyo, Amatekpor, and Adjadeh 2020). Also, root distribution and activity can significantly impact OC content across depths (Yao et al. 2019). Roots contribute directly to soil OC through the deposition of dead root material and root exudates, and indirectly by enhancing soil microbial activity and organic matter decomposition (Al-Traboulsi, Wilsey, and Potvin 2021). As root density typically decreases with soil depth, so does the input of OC (Wang et al. 2021). Lastly, the impact of human activities, such as agriculture and land management practices, should not be overlooked. Practices like deep plowing can redistribute OC within the soil profile, potentially leading to a more even distribution of OC across depths or increased OC at deeper layers (Souza et al. 2023).

The observed decline in soil organic carbon (SOC) with depth carries significant implications for soil management, particularly in regions vulnerable to climate change. As SOC is most concentrated in the topsoil, this underscores the importance of topsoil preservation in carbon sequestration efforts. Managing soils with reduced tillage practices or cover cropping could help mitigate SOC losses by stabilizing the topsoil and enhancing carbon storage. Moreover, in regions where SOC decreases sharply with depth, strategies to enrich subsurface layers with organic matter, such as deep-rooted plants, could improve soil fertility and resilience against erosion.

The results of average SOC content in the fine-earth fraction by depth, in kg/m^2, can be compared with values presented in the study conducted by FAO in 2002, for depths of 0–30 cm, 0–100 cm, 0–200 cm, and for the soil units Andosol, Chernozem, Ferralsol, Lithosol, Nitosol, Podzol, Rendzina, Vertisol, Xerosol, and Yermosol. The average SOC content in the fine-earth fraction for the soil units mentioned in the cited study shows an increasing trend as the depth interval increases. As mentioned earlier, this study reveals that the soil units Ferralsol, Nitosol, and Podzol exhibit an increasing trend in average SOC content in the fine-earth fraction as depth increases. Thus, it is observed that the trend of SOC content with depth is consistent with the study conducted by FAO. It is also worth mentioning that the FAO study generally reports contents more than twice as high as those obtained in this study, except for the shallowest depth (0–30 cm) in the Nitosol soil unit. On the other hand, it also reveals that the soil units Andosol, Chernozem, Vertisol, and Xerosol exhibit a decreasing trend in average SOC content in the fine-earth fraction as depth increases. Therefore, it is observed that the trend of SOC content with depth is inconsistent with the study conducted by FAO, as presented in Table 4. It is also worth mentioning that the FAO study generally reports contents more than twice as high as those obtained in this study, except for the shallowest depth (0–30 cm) in the Chernozem, Vertisol, and Xerosol soil units. Due to the unavailability of data regarding results by depth, it was not possible to perform a comparative analysis for the Lithosol, Rendzina, and Yermosol soil units.

The results provide a detailed overview of the average content of organic carbon (OC) in various soil units and at different depths, comparing the results of the present study with those obtained from an FAO study. Upon analyzing the data, it becomes apparent that, overall, the content of OC in the depths studied is lower in the present study than the values presented by the FAO. In the case of Andosols, the difference is substantial. The present study records an average OC content ranging from 3.99 to 4.29 kg/m^2 at different depths, while the FAO study reports considerably higher values, reaching 31.00 kg/m^2 at a depth of 0–200 cm. Similarly, in Chernozems, Ferralsols, Nitosols, Podzols, Vertisols, and Xerosols, the average content of OC is consistently lower in the present study, across all analyzed depths. This suggests a possible decrease in OC content in these soils if we assume that the FAO data were collected prior to the present study. Interestingly, Lithosols and Rendzinas present inconsistent data, making the comparison more complex. In the case of Lithosols, the present study records OC contents at depths ranging from 0–100 cm to 0–2590 cm, while the FAO only provides data for a depth of 0–30 cm. The reverse is true for Rendzinas, where the present study does not provide any data, while the FAO reports an OC content of 13.30 kg/m^2 at a depth of 0–30 cm. The general trend in the data is a lower content of OC in the depths studied in the present study compared to the FAO study. This trend could reflect various situations, such as changes in land use, management practices, or even natural temporal and spatial variations. For a more precise interpretation, it would be helpful to have access to additional information, such as the time between the two studies and the specific environmental conditions of each study location.

Table 4. Results of the average OC content in the fine-earth fraction per depth and per soil unit from the present study compared to the study presented by FAO, where (*) corresponds to the results of the current study, and (**) corresponds to the results presented by FAO.

	Average content of OC in the fine earth fraction by depth (kg/m^2)				
Soil units	0–30 cm	0–100 cm	0–200 cm	0–2590 cm	Source
Andosol	4.29	3.99	4.14	4.14	(*)
	11.40	25.40	31.00	-	(**)
Chernozem	6.52	4.98	4.10	4.11	(*)
	6.00	12.50	19.60	-	(**)
Ferralsol	2.34	2.58	2.63	2.63	(*)
	5.70	10.70	16.90	-	(**)
Lithosol	-	3.75	4.94	4.94	(*)
	3.60	-	-	-	(**)
Nitosol	3.21	4.19	4.40	4.40	(*)
	4.10	8.40	11.30	-	(**)
Podzol	2.85	3.15	4.87	4.87	(*)
	13.60	24.20	59.10	-	(**)
Rendzina	-	-	-	-	(*)
	13.30	-	-	-	(**)
Vertisol	4.76	4.47	3.95	3.95	(*)
	4.50	11.10	19.10	-	(**)
Xerosol	1.82	1.46	1.55	1.55	(*)
	2.00	4.80	8.70	-	(**)
Yermosol	-	-	-	-	(*)
	1.30	3.00	6.60	-	(**)

The results, as presented in Table 4, reveal intriguing patterns of OC distribution that are worthy of further analysis and discussion. Firstly, it is notable that the average OC content varies significantly between different soil types, with Andosols and Chernozems showing the highest content in our study, and Lithosols and Xerosols showing the lowest. This may be attributable to the specific characteristics of these soil types, such as their composition, structure, and the local climatic conditions under which they form. A comparison with the FAO study reveals some discrepancies, which may be attributed to differences in methodologies, sampling locations, or temporal variations in soil OC content. For instance, in the case of Andosols, our study found an average OC content of 4.14 kg/m^2 in the 0–2590 cm depth range, whereas the FAO study reported values as high as 31.00 kg/m^2 for depths up to 200 cm. Similarly, for Podzols, our study found an average OC content of 4.87 kg/m^2, while the FAO study reported a considerably higher value of 59.10 kg/m^2 at 200 cm depth.

The depth-related variations in OC content are another significant aspect of our findings. In general, our study found that the OC content decreases as the depth increases, which is consistent with the understanding that organic matter, and hence OC, is more concentrated in the upper soil layers. However, the exact patterns of depth-related variations differed between soil types. In Chernozems, for instance, the OC content decreased from 6.52 kg/m^2 at 0–30 cm to 4.10 kg/m^2 at 0–200 cm, whereas in Ferralsols, it slightly increased from 2.34 kg/m^2 to 2.63 kg/m^2 over the same depth range.

These results raise interesting questions about the factors influencing the distribution of OC in soils. Soil depth is obviously a major factor, with the amount of OC generally decreasing with increasing depth. This could be due to the lower presence of plant roots and microbial activity in deeper layers, as well as the lower availability of fresh organic matter for decomposition. Soil type is another important factor, with certain soil types, such as Andosols and Chernozems, generally containing more OC than others. This could be related to the specific properties of these soils, such as their texture, structure, pH, and mineral composition, which can affect the decomposition rate of organic matter and the capacity of soils to store OC.

Variations in climate and land use between the sampling locations of different soil types could also contribute to the observed differences in OC content. For instance, soils in colder or drier regions may have lower decomposition rates, leading to higher OC content. Similarly, soils under forests or grasslands may contain more OC than those under agricultural or urban use due to differences in vegetation cover, organic matter input, and soil management practices. As can be seen, these findings highlight the complex and multifaceted nature of soil OC distribution, underscoring the need for further research to elucidate the underlying mechanisms and to refine our predictions of soil carbon sequestration under future climate and land use scenarios. Also, SOC variability plays a critical role in determining soil fertility, especially in regions facing food insecurity. In Africa, where over 868 million people are affected by food insecurity, enhancing SOC through sustainable agricultural practices is crucial for increasing crop yields and soil productivity. Practices such as agroforestry and organic farming can increase SOC levels, improving the soil's nutrient-holding capacity and reducing the reliance on chemical fertilizers, which are often inaccessible to smallholder farmers in food-insecure regions.

Conclusions

This research underscores the essential need for maintaining robust and high-quality soil databases, emphasizing the importance of continual updating and expansive soil monitoring networks across nations. This ensures the protection and enhancement of the world's soil data bank. The data provided in this study offer significant insights into the carbon sequestration potential of various soil units, as detailed in the provided tables. Our analysis of 51,507 soil profile layers and 6,197 soil profiles, classified into 34 soil units, revealed that, generally, as the depth increases, both the gravimetric and average organic carbon (OC) content decrease. Notably, some soil units exhibited an increase in average OC content at greater depths, contrary to the overall trend.

However, it is crucial to recognize that soil carbon content is predominantly determined by enduring factors linked to soil formation, such as soil bulk density, which can be significantly impacted by changes in soil use and management practices. While the data presented reveals significant trends in SOC distribution across depths and regions, the practical implications extend beyond the data itself. For long-term soil sustainability, understanding these SOC trends is essential for informing soil conservation strategies. Policymakers, farmers, and land managers must interpret these trends within the context of improving soil health, enhancing carbon sequestration, and sustaining agricultural productivity under changing climate conditions. This calls for an interdisciplinary approach where statistical findings are used to shape actionable policies and land management practices.

The variability in SOC content across regions has critical implications for soil resilience in areas facing conflict or environmental extremes. In conflict-affected regions such as Ukraine or food-insecure countries like Syria, Tunisia, and Ghana, where agricultural systems are already under stress, SOC loss could further exacerbate food insecurity. In these regions, preserving SOC through soil conservation techniques can improve soil structure and increase agricultural output. Furthermore, in carbon-rich regions like the Amazon, careful soil management is essential for maintaining the global carbon balance, as any reduction in SOC could have widespread consequences for climate regulation.

These findings highlight the need to integrate SOC management into broader climate adaptation strategies. For instance, the decreasing SOC content with depth reflects a challenge for sustaining soil fertility and long-term agricultural productivity. Practices such as regenerative agriculture, which focuses on improving soil health, can be instrumental in reversing SOC loss trends. Additionally, carbon sequestration potential is highly dependent on land use. Forested areas and grasslands, with their deeper-rooting systems and less soil disturbance, can maintain SOC levels better than agricultural lands. Addressing land use practices is essential for enhancing both carbon storage and food security.

Regular updates and constant evaluation of soil carbon trends are, therefore, indispensable in understanding and enhancing soil carbon sequestration potential. These findings offer valuable insights for climate change mitigation strategies and sustainable land use practices. The data presented in this study offers a vital resource for policymakers to design region-specific soil management strategies. Geospatial analysis of SOC trends can inform localized practices such as targeted reforestation, erosion control, and the implementation of regenerative agriculture. These practices can be incorporated into national soil conservation policies and international climate agreements, ensuring that soil management plays a pivotal role in climate adaptation and mitigation strategies. Future research should focus on the interactions between SOC and soil bulk density under various climate scenarios to develop robust climate mitigation strategies. Moreover, understanding the relationship between SOC and biodiversity in fragile ecosystems can inform efforts to protect these regions from degradation. Investigating how regenerative agricultural practices can enhance SOC levels in regions under environmental stress, such as semi-arid areas or conflict zones, will be critical for supporting global food security and sustainability efforts.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

L.J.R.N. was supported by proMetheus, Research Unit on Energy, Materials and Environment for Sustainability—UIDP/05975/2020, funded by national funds through FCT—Fundação para a Ciência e Tecnologia. Fundacao para a Ciencia e Tecnologia [UIDP/05975/2020].

Author contributions

Conceptualization, C.I.D.R., M.B. and L.J.R.N.; methodology, M.B. and L.J.R.N.; software, C.I.D.R., M.B. and L.J.R.N.; validation, M.B. and L.J.R.N.; formal analysis, C.I.D.R., M.B. and L.J.R.N.; investigation, C.I.D.R., M.B. and L.J.R.N.; resources, C.I.D.R., M.B. and L.J.R.N.; data curation C.I.D.R., M.B. and L.J.R.N.; writing – original draft preparation, C.I.D.R., M.B. and L.J.R.N.; writing – review and editing, M.B. and L.J.R.N.; visualization, C.I.D.R., M.B. and L.J.R.N.; supervision, M.B. and L.J.R.N.; project administration, L.J.R.N. All authors have read and agreed to the published version of the manuscript.

Data availability statement

Data will be made available upon request to correspondent author.

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