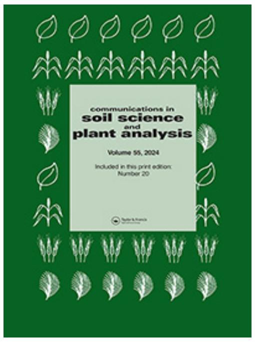

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Soil Vertical Distribution of Organic Carbon and Sequestration Potential in Ponte de Lima (Alto Minho Region, Northern Portugal)

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ABSTRACT
Understanding the vertical distributions of organic carbon (OC) is crucial for predicting and simulating the influences of soil units on the terrestrial carbon cycle. The OC in the fine earth fraction was calculated for the soil units Anthrosols, Cambisols, Fluvisols, Leptosols, and Regosols in the municipality of Ponte de Lima, Portugal, at depths of 0–30 cm, 0–100 cm, 0–200 cm, and 0–2590 cm. In the study area, over 40% of the OC is concentrated in the Regosol unit, followed by the Anthrosols with over 23% OC at all depths, and the Leptosols with over 22% OC at all depths. The soil units Cambisols and Fluvisols have a lower representation in the territory, with values below 1.5% and 6.5% respectively at all depths. The obtained results contribute to assessing the potential of the soil units present in the municipality to sequester CO_2, promoting the development of carbon inventories and analyzing the distribution of OC through accurate and reliable estimates of current C reserves as an essential tool for analyzing and modeling the effects of different factors involved in the potential of soil OC sequestration.

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Carbon sequestration; organic carbon; Ponte de Lima; soil units; vertical distribution

Introduction

Over the centuries, the main natural sinks of carbon dioxide (CO_2) were associated with absorption by oceans, plants, and soils (IPCC et al. 2021). Considering that more than two-thirds of terrestrial organic carbon (OC) reserves are found in soils (IPCC et al. 2000; Solomon et al. 2007), representing the largest terrestrial carbon reservoir, which includes soil OC (approximately 1526 PgC) and inorganic carbon (IC) in soils (approximately 940 PgC) (Lal et al. 2021). Soils have the ability to store carbon for long periods, and significant changes in carbon reservoirs could significantly alter atmospheric CO_2 concentrations. Furthermore, maintaining adequate carbon levels in these reservoirs is essential for reducing the risks of erosion and degradation, retaining water and nutrients, and improving soil structure (Lal 2004).

There has been extensive discussion in the scientific literature about the importance of OC in the soil and its potential as a sink for atmospheric CO_2. There is a growing concern regarding the potential consequences of climate change on soil processes, coupled with a desire to develop methods, stimulate experimental research, and develop models and theories to increase the capacity of the soil to sequester

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carbon (Guo and Gifford 2002; Lal 2004, 2008; Post and Kwon 2000; Post et al. 2004). Undoubtedly, in today's world marked by climate change, this topic deserves special attention. As carbon sequestration in the soil is potentially finite, not permanent (IPCC et al. 2000), and challenging to quantify and verify over the long term, it can be considered a risky strategy for mitigating climate effects compared to direct emissions reduction. However, in the short term, it can be crucial for reducing atmospheric CO_2 concentrations (Smith 2004). In recent years, there has been an increasing need for accurate information on OC concentrations in soils at global, European, national, or regional levels, given the significance of carbon reserves for the sustainable use of natural resources.

In addition to the current concerns about environmental issues such as soil degradation and contamination, information about OC reserves is necessary to assess the potential of soils to sequester CO_2, as required by the Kyoto Protocol and the United Nations Framework Convention on Climate Change, which mandate national inventory reports on C reserves (Muñoz-Rojas et al. 2012). This necessitates accurate and reliable estimates of current C reserves (Amézketa 1999; Percival, Parfitt, and Scott 2000; Torn et al. 1997). In this regard, C inventories and analysis of OC distribution are essential tools for modeling the effects of different factors involved in soil OC sequestration potential. It is important to note that there is a consensus regarding the relationship between soil type and OC storage at multiple scales and under different climatic conditions. During pedogenesis, weathering chemical reactions lead to changes in soil mineralogy composition, which strongly influence mineral surface reactivity and C storage, resulting in categorically described soil types. In contrast to climate, vegetation, and parent material, which can serve as indicators for OC storage at larger scales, C reserves can be stratified according to soil type even at smaller scales (local to sub-regional) (Wiesmeier et al. 2019). Numerous studies have revealed a predominant influence of soil type on soil OC reservoirs, both at the surface and subsurface (Chaplot, Bouahom, and Valentin 2010; Grimm et al. 2008; Hobley et al. 2015; Vasques et al. 2010; Xiong et al. 2014).

Soil type is not an independent controlling factor, but rather integrates a set of factors such as climate, parent material, and topography that are related to properties directly affecting the soil's potential to store C, particularly soil moisture regime and texture. If information on soil properties such as texture and moisture is not available, soil type can be a suitable indicator for soil OC storage, encompassing a wide range of decisive factors. Therefore, the present study aims to calculate average values of gravimetric OC content and average content at different depths for the soil units present in the municipality of Ponte de Lima.

Materials and methods

Area under study

Located in the Northern region of mainland Portugal, the municipality of Ponte de Lima is part of the district of Viana do Castelo, encompassed within the NUTS II – Norte and NUTS III – Alto Minho regions. Based on the available data and the classification of the pedologic units as shown in the Soil Map (Figure 1), it is observed that the Municipality of Ponte de Lima comprises Anthrosols (112,846,174.1 m^2), Cambisols (3,209,142.6 m^2), Fluvisols (21,010,864.2 m^2), Leptosols (43,596,653.8 m^2) and Regosols (136,466,002.8 m^2).

Database

Framework

Due to the costs involved in maintaining and archiving soil data on paper, as well as the physical deterioration or disintegration of these data, global soil resources data, information, and knowledge are fragmented and even at risk of being lost (Arrouays et al. 2017). 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

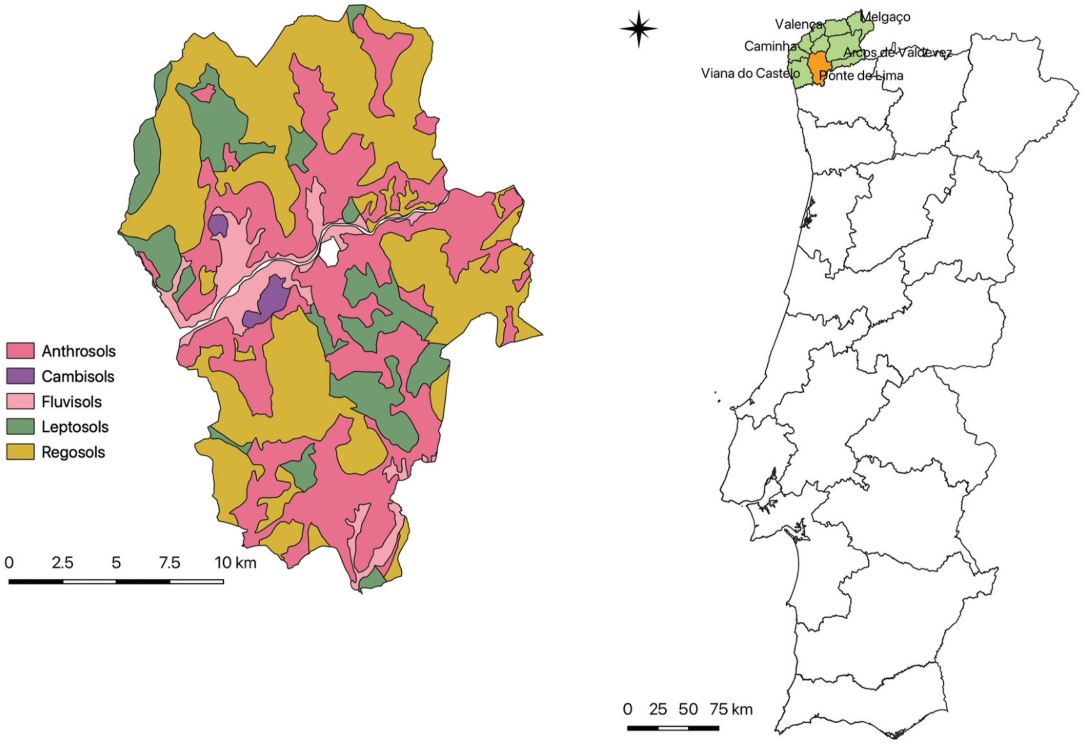

Figure 1. Geographical framework and soil chart of Ponte de Lima.

Service (WoSIS) project since the release of the first dataset in 2016 (Batjes et al. 2017). The analysis conducted here is based on the latest update of the World Soil Database, specifically WoSIS from 2019 (Batjes et al. 2017), which provides standardized and quality soil profile data to support digital soil mapping and large-scale environmental applications.

Since soil profile data was provided by various entities, WoSIS took into account measures of soil data quality, standardization of soil property definitions, soil property values (and units of measurement), and descriptions of soil analytical methods. Currently, this database gathers several soil chemical properties, including OC, total carbon, total equivalent carbonate, total nitrogen, phosphorus (extractable P, total P, and P retention), soil pH, cation exchange capacity, and electrical conductivity. This database also collects various physical soil properties, grouped according to analytically comparable procedures (aggregates), including soil texture (sand, silt, and clay), bulk density, coarse fragments, and water retention. At the geographical level, measures of geographic precision of point data are provided, as well as a first approximation of the uncertainty associated with the operatively defined analytical methods for potential digital soil mapping and subsequent terrestrial system modeling. Standardized datasets derived from the WoSIS database are distributed in two ways. The most recent version used in this analysis, WoSIS, consists of over 202,000 georeferenced profiles originating from six continents and 177 countries. The data is accessible through the International Soil Reference and Information Center (available at https://www.isric.org/, accessed on May 30, 2023).

Soil classification

For each soil profile, its original classification, according to the FAO, is provided and its respective version is presented, if they have been specified in the original databases. In the WoSIS database were found 21,714 soil profiles that have a classification regarding the soil unit. In Table 1, which follows, the 34 soil units are displayed by the number of soil profiles.

Table 1. Number of soil 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

In particular, for the purposes of this study, only the soil units present in the area of investigation will be considered, namely, Anthrosol (214 soil profiles), Cambisol (2584 soil profiles), Fluvisol (942 soil profiles), Leptosol (421 soil profiles), and Regosol (1578 soil profiles), totaling 5739 soil profiles.

Soil density

For each soil profile and, particularly, for each soil profile layer, data on the apparent density of the fine earth fraction, oven-dried (kg/dm^3), is available. In total, there are 123,585 data entries distributed across 24,571 soil profiles, determined at different soil profile layers. For the Anthrosol soil unit, given the absence of density data for each soil profile layer, the average density resulting from all data on the apparent density of the fine earth fraction, oven-dried, was taken into account. This density is 1.36 kg/dm^3, across the 720 soil profile layers. For the Cambisol soil unit, there are 649 available data entries on the apparent density of the oven-dried fine earth fraction, with the minimum density being 0.04 kg/dm^3, the maximum 1.93 kg/dm^3, and the average 1.37 kg/dm^3. For the Fluvisol soil unit, there are 134 available data entries on the apparent density of the oven-dried fine earth fraction, with the minimum density being 0.59 kg/dm^3, the maximum 1.78 kg/dm^3, and the average 1.26 kg/dm^3. For the Leptosol soil unit, there are 64 available data entries on the apparent density of the oven-dried fine earth fraction, with the minimum density being 0.27 kg/dm^3, the maximum 1.78 kg/dm^3, and the average 1.27 kg/dm^3. For the Regosol soil unit, there are 196 available data entries on the apparent density of the oven-dried fine earth fraction, with the minimum density being 0.10 kg/dm^3, the maximum 1.79 kg/dm^3, and the average 1.42 kg/dm^3.

Organic carbon (OC)

The gravimetric content of OC in the fine earth fraction (g/kg), is one of the parameters with the most information in the WoSIS Latest database, totaling 458,406 data points distributed across 121,509 soil profiles, determined at different depths. The various depths are presented in measurement intervals (upper layer depth and lower layer depth), in cm, ranging between 0 cm and 2590 cm. For the soil units under study, namely, Anthrosol, Cambisol, Fluvisol, Leptosol and Regosol, there are available 12,159 data points related to the gravimetric content of OC in the fine earth fraction, specifically 720, 6496, 2768, 311 and 1864, respectively.

Data processing

We initiated the data processing with the QGIS software. This application facilitated the identification, selection of resources, and viewing of attribute tables, allowing to gather and handle information from three different layers: ms:wosis_latest_profiles, ms:wosis_latest_bdfiod, and ms:wosis_latest_orgc.

Each layer offers specific soil-related data. The first layer, ms:wosis_latest_profiles, supplies details about the soil profile, like the identification number, its geographical location (continent, country), and classification based on FAO standards. The second layer, ms:wosis_latest_bdfiod, gives information about the apparent density of the fine earth fraction, oven-dried, linked to each soil profile and its layers. The third layer, ms:wosis_latest_orgc, includes information about the gravimetric content of OC in the fine earth fraction, such as depth and OC value. After examining the attribute tables from these layers, the data were extracted into an Excel file for further processing. The initial analysis of the data from the three layers enabled to correlate the soil classification to the gravimetric content of OC in the fine earth fraction by depth, as well as the apparent density of the fine earth fraction with the gravimetric content of OC at varying depths.

To calculate the average OC content in the fine earth fraction by depth in kg/m^2, the gravimetric content of OC (g/kg) was multiplied by the apparent density (kg/dm^3) and the sample depth (cm). This led to the creation of a consolidated database containing information about soil classification, apparent density, gravimetric content of OC by depth, and average OC content by depth. Finally, using Excel's pivot table tool, the data were simplified and summarized for the studied soil units. The depths were categorized into intervals (0–30 cm, 0–100 cm, 0–200 cm, 0–2590 cm) and computed the average values for each soil unit, regarding both the gravimetric content of OC and the average OC content by depth.

Results

Gravimetric content of OC in the fine earth fraction

The results pertaining to the gravimetric content of OC in the fine earth fraction, in g/kg, shown in Table 2, were calculated using the averages of 12,159 data points related to the gravimetric content of OC in the fine earth fraction distributed across soil profile layers categorized for the 5 soil units, and distributed by depths, specifically, 0–30 cm, 0–100 cm, 0–200 cm, and 0–2590 cm. The results indicated that 4 of the 5 soil units exhibited a decreasing trend in the gravimetric content of OC in the fine earth fraction as depth increased, namely, Andosol, Cambisol, Fluvisol, and Regosol. The results also allowed the observation that the Leptosol soil unit shows a decreasing trend in the gravimetric content of OC in the fine earth fraction up to a depth of 0–200 cm, with the content remaining constant beyond this depth.

For all soil units, it is apparent that the OC content tends to decrease with the increase in soil depth, reflecting the higher content of organic matter in the upper layers. However, this trend varies among the different soil types. Leptosols appear the richest in OC at all depths, with 38.94 g/kg at 0–30 cm, decreasing slightly to 28.10 g/kg at 0–2590 cm, suggesting a relatively uniform distribution of OC throughout the soil profile. In contrast, Cambisols, despite showing a high OC content at 0–30 cm (22.00 g/kg), exhibit a steeper decline, reaching 12.14 g/kg at 0–2590 cm. This may indicate a more active process of decomposition or mineralization of organic matter in these soils. Fluvisols show intermediate values, with 16.63 g/kg at 0–30 cm and 11.56 g/kg at 0–2590 cm. Anthrosols and Regosols display a similar pattern to Fluvisols, albeit with lower values, particularly Regosols that show the least

Table 2. Gravimetric content of OC 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
Anthrosol	13.21	9.97	9.58	9.55
Cambisol	22.00	14.12	12.15	12.14
Fluvisol	16.63	12.25	11.57	11.56
Leptosol	38.94	29.11	28.10	28.10
Regosol	14.13	9.77	8.83	8.79
Average content	20.98	15.05	14.05	14.03

OC content at all depths. The average OC content for all soil categories decreases from 20.98 g/kg at 0–30 cm to 14.03 g/kg at 0–2590 cm. These results provide valuable insights into the distribution and availability of OC across different soil types throughout the soil profile, factors that are crucial for understanding the role of soil as a carbon sink and its potential in mitigating climate change.

Average content of OC in the fine earth fraction

The most commonly determined results are expressed per unit surface, specifically in kg/m^2 or t/ha. In this regard, using the values of density and sampling depth, the average content of OC in kg/m^2 was calculated. The results regarding the average OC content in the fine earth fraction, in kg/m^2, shown in Table 3 and schematized in Figure 2 were derived from the averages of 1762 data points related to the average OC content in the fine earth fraction distributed across soil profile layers, categorized into 5 soil units, distributed across depths, namely 0–30 cm, 0–100 cm, 0–200 cm, and 0–2590 cm. The obtained results revealed that 2 out of the 5 soil units exhibit a decreasing trend in average OC content in the fine earth fraction as the depth increases, specifically the Cambisol unit at all depths and the Regosol unit up to a depth of 0–200 cm, remaining constant beyond this depth. The results also revealed that 3 out of the 5 soil units show an increasing trend in average OC content in the fine earth fraction as the depth increases, namely the Anthrosol unit up to a depth of 0–200 cm and remaining constant beyond this depth; the Leptosol unit up to a depth of 0–100 cm, slightly decreasing at a depth of 0–200 cm and remaining constant beyond this depth; the Fluvisol unit up to a depth of 0–100 cm, decreasing beyond this depth. It is important to note that, due to the lack of density data for the Anthrosol unit, the average density resulting from all data of apparent density of the fine earth fraction, dried in an oven, was considered, resulting in a density of 1.36 kg/dm^3 in the 720 soil profile layers. For the study area, the soil units that exhibit the highest average OC content in the fine earth fraction at all depths are the Leptosol and Regosol units.

The average content (kg/m^2) for all soil units shows a decreasing trend across the depth ranges (Table 3 and Figure 2). Anthrosols reveal a steady increase in the average OC content from 2.48 kg/m^2 at the 0–30 cm depth range to 2.80 kg/m2 at both the 0–200 cm and 0–2590 cm depth ranges, indicating an accumulation of OC with increasing depth. Cambisols, however, show a different pattern. Starting with a relatively high content of 3.78 kg/m^2 at the 0–30 cm depth, the OC content decreases with depth to 3.05 kg/m^2 at the 0–2590 cm depth range. This suggests a decrease in OC with increasing depth. Fluvisols have a relatively consistent OC content, starting with 3.19 kg/m^2 at the 0–30 cm depth, then slightly increasing to 3.42 kg/m^2 at the 0–100 cm depth range, and marginally decreasing to 3.37 kg/m^2 by the 0–2590 cm depth range. Leptosols show the highest OC concentrations among all the soil units across all depths, starting with 5.96 kg/m^2 at the 0–30 cm depth range and slightly increasing to 6.07 kg/m^2 at the 0–100 cm depth range, then leveling off at 5.94 kg/m^2 for both the 0–200 cm and 0–2590 cm depth ranges. Regosols show a decreasing trend in OC content, from 4.08 kg/m^2 at the 0–30 cm depth to 3.45 kg/m^2 at both the 0–200 cm and 0–2590 cm depth ranges. This pattern indicates a reduction in OC content with increasing depth. The average OC content across all the soil units and depths starts with 3.90 kg/m^2 at the 0–30 cm depth range, decreases slightly to 3.82 kg/m^2 at the 0–100 cm depth, and further decreases to 3.73 kg/m^2 and

Table 3. Average OC content in the fine earth fraction by depth and soil unit.

	Average OC content in the fine earth fraction by depth (kg/m^2)			
Soil units	0–30 cm	0–100 cm	0–200 cm	0–2590 cm
Anthrosol	2.48	2.71	2.80	2.80
Cambisol	3.78	3.27	3.06	3.05
Fluvisol	3.19	3.42	3.40	3.37
Leptosol	5.96	6.07	5.94	5.94
Regosol	4.08	3.61	3.45	3.45
Average content	3.90	3.82	3.73	3.72

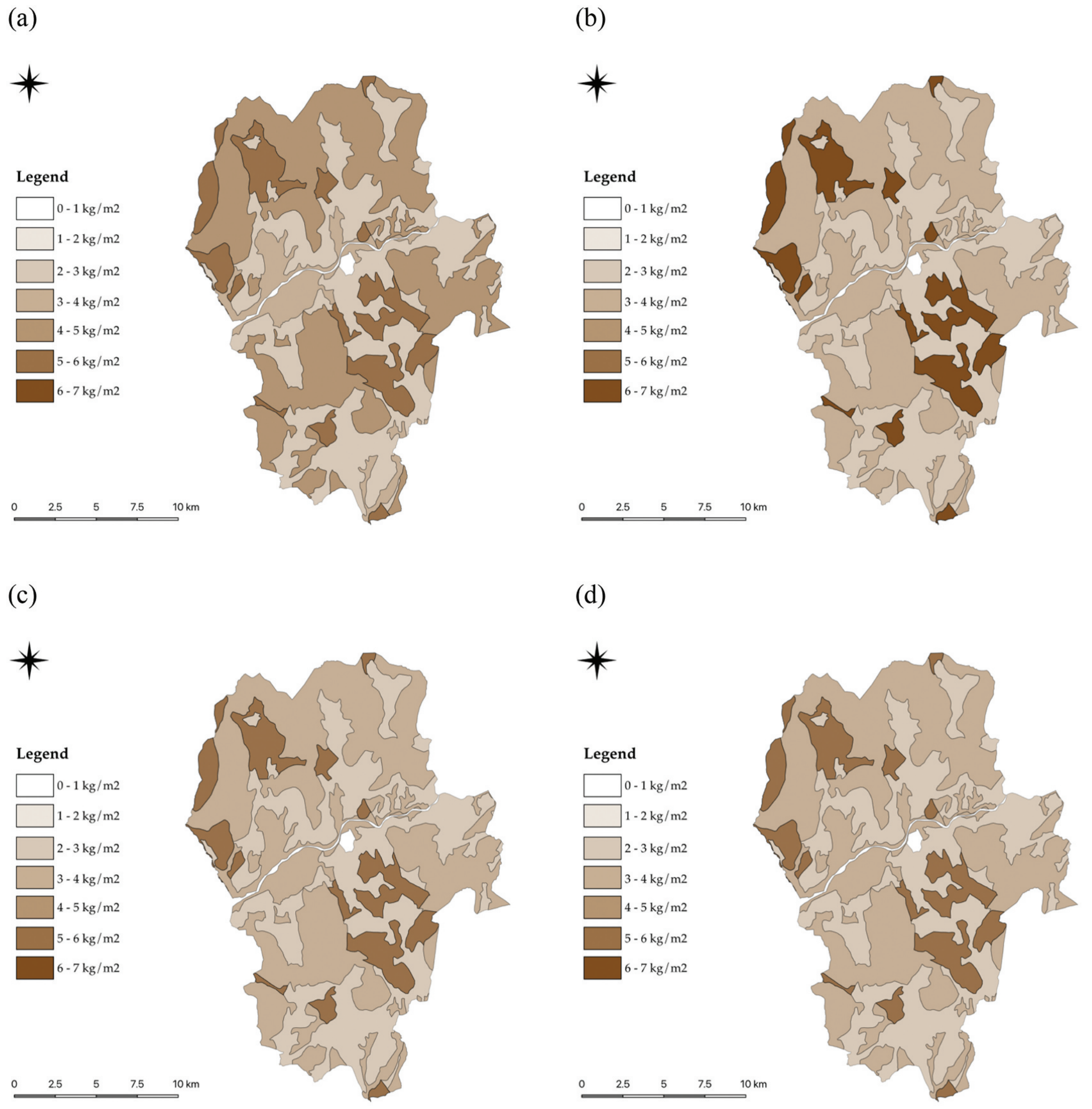

Figure 2. Average content of organic carbon (OC) in the fine earth fraction in Ponte de Lima: (a) depth of 0–30 cm; (b) depth of 0–100 cm; (c) depth of 0–200 cm; (d) depth of 0–2590 cm.

3.72 kg/m^2 at the 0–200 cm and 0–2590 cm depth ranges, respectively. This reveals a slight but consistent decrease in the average OC content with increasing depth across all the soil units.

OC concentration in the fine earth fraction in Ponte de Lima

To calculate the OC in the fine earth fraction in Ponte de Lima, the area of each soil unit (m^2) was multiplied by the average OC concentration in the fine earth fraction (kg/m^2). Thus, the OC for Ponte de Lima was determined by depth (Table 4).

In the top 30 cm depth, the highest OC content was observed in the Regosol unit with 557,075 Mg, followed by the Anthrosol unit with 280,000 Mg. The Leptosol unit had 260,038 Mg of OC, while the Fluvisol and Cambisol units had 67,000 Mg and 12,130 Mg respectively. As the depth increased to 0–100 cm, 0–200 cm, and 0–2590 cm, the total OC content gradually decreased for all soil units.

Table 4. OC in the fine earth fraction by depth and soil unit in Ponte de Lima.

	OC in the fine earth fraction by depth (Mg)			
Soil units	0–30 cm	0–100 cm	0–200 cm	0–2590 cm
Anthrosol	279,641	305,966	315,419	315,570
Cambisol	12,130	10,505	9,814	9,785
Fluvisol	66,934	71,911	71,403	70,875
Leptosol	260,038	264,484	259,092	259,092
Regosol	557,075	493,198	471,311	471,311
Total	1,175,818	1,146,064	1,127,039	1,126,633

However, the Regosol unit maintained the highest OC content across all depths, with 493,198 Mg at 0–100 cm, 471,311 Mg at 0–200 cm, and 471,311 Mg at 0–2590 cm. The Leptosol unit showed consistent OC content of around 260 Mg for all depths, while the Anthrosol unit ranged from 300 to 315 Mg. The Fluvisol unit displayed a relatively stable OC content around 71 Mg across all depths, and the Cambisol unit ranged from 10 to 11 Mg. Overall, when considering all depths, the Regosol unit had the highest total OC content with 471,311 Mg, followed by the Anthrosol unit with 316,000 Mg. The unit Leptosol had a total OC content of 259,092 Mg, while the Fluvisol and Cambisol units had 71,000 Mg and 10,000 Mg respectively. These results indicate that the Regosol and Leptosol units have the highest potential as carbon sinks, as they consistently maintain substantial OC content across different depths. The Anthrosol unit also shows promise in carbon sequestration.

Discussion

Organic carbon constitutes a major component of the soil and plays a critical role in ecosystems, both as a carbon sink through storage and sequestration, as well as by contributing to soil fertility and agricultural productivity. The distribution and quantity of OC in the soil can be influenced by various factors, including soil type, vegetation, climate, land use, and soil management practices. The results obtained from the soil analysis of the Ponte de Lima region, in particular the Anthrosol, Cambisol, Fluvisol, Leptosol, and Regosol soil units, demonstrate significant differences in their potential as carbon sinks. Notably, as the depth increases, the average content observed for all soil units exhibits a decreasing trend, and consequently, OC decreases. In the Ponte de Lima municipality, due to its representative area, for all depths, over 40% of the OC concentrates in the Regosols. The Anthrosols represent more than 23% of OC at all depths, followed by Leptosols with over 22% of OC at all depths. The Cambisol and Fluvisol soil units represent a lesser proportion of the territory, demonstrating values lower than 1.5% and 6.5%, respectively, at all depths.

There is a decline in OC content with the increase in depth across all soil units. This pattern can be explained by the fact that OC is typically more concentrated in the topsoil layers where organic matter decomposition is most active. Regosols present the highest quantity of OC at all depths, followed by Anthrosols and Leptosols. The high capacity of these soils to store OC may be associated with their specific composition and structure, promoting OC stability and retention. This finding suggests that Regosols, Leptosols, and Anthrosols have significant potential to function as carbon sinks. Conversely, Cambisols and Fluvisols demonstrate a lower content of OC at all depths. In Cambisols, this situation may be influenced by their sandy texture, promoting OC mineralization and release. Fluvisols are usually found in flood-prone areas, where the constant sediment deposition can dilute the amount of OC. The importance of these soils as carbon sinks lies in their capacity to mitigate climate change by storing carbon. This process reduces the amount of carbon dioxide in the atmosphere, one of the main greenhouse gases. In this context, it’s crucial to emphasize that the proper management of these soils, through sustainable land use practices, can contribute to the conservation and increase of their potential as carbon sinks.

Given the emerging scenario of climate change and its widely recognized consequences, agriculture in Ponte de Lima, like in many other regions, faces an uncertain future. This future will require significant adaptations to ensure that agriculture remains viable while also preserving the environment. In this context, proper soil management becomes imperative as these soils play a vital role in mitigating climate change through their capacity to function as carbon sinks. The practice of no-till farming is one of the techniques that can be adopted. This involves planting directly over the residues of the previous crop, minimizing soil disturbance, and consequently, the release of OC to the atmosphere. This technique, in addition to contributing to maintaining and increasing the OC content in the soil, also helps to preserve its structure and promote its water retention capacity. Crop rotation, meadows and pastures are other practices that can be adopted with mutual benefits for agriculture and climate change mitigation. In addition to increasing biological diversity and improving soil health, it can also contribute to increasing the OC content since different crops have different abilities to fix and store carbon. Incorporating organic residues into the soil is another practice that can be adopted. This practice involves returning to the soil the organic residues generated by agricultural activity, such as manure or harvest residues. These residues, when when humified, can contribute to increasing the OC content in the soil, improving its fertility and, at the same time, functioning as carbon sinks.

This study highlights the importance of Ponte de Lima's soils as carbon sinks, potentially instrumental in mitigating climate change. These soils can capture and store carbon, thus contributing to the reduction of carbon dioxide concentration in the atmosphere, one of the main greenhouse gases. However, it's essential to underscore that the capacity of these soils to perform this role is not merely innate but highly dependent on the implemented management practices. Proper soil management, i.e., the implementation of agricultural techniques and land use practices that are sustainable and respect the soil's capacity, is crucial for maintaining and even increasing its carbon sequestration potential. Inappropriate soil use, on the other hand, can lead to soil degradation, loss of organic matter, and consequently, a reduction in its carbon storage potential. The climate change landscape imposes a new challenge to soil management. Adapting to this new reality means acknowledging the need for more sustainable soil management practices, capable of preserving and increasing the amount of carbon stored in the soil. This entails responsible agricultural practices that minimize soil disturbance, promote soil cover and crop rotation, and foster the addition of organic matter to the soil. Therefore, the results of this study not only underline the crucial role of Ponte de Lima's soils as carbon sinks but also highlight the need for proper soil management, aimed at conserving and enhancing this capacity. This will require a collective effort from farmers, land managers, policymakers, and the scientific community, guided by a shared commitment to sustainability and climate change mitigation.

Conclusion

This study emphasizes the fundamental importance of maintaining detailed and high-quality standardization of soil databases. To ensure the protection and enhancement of the earth's soil resources, it is crucial to continuously update these databases and develop comprehensive soil monitoring networks across all countries. This process guarantees the upkeep and expansion of inventories within the global soil data bank. The findings herein provide a significant contribution toward evaluating the potential of the soil units in the municipality of Ponte de Lima to sequester CO_2. This work aids the progression of carbon inventories and the analysis of OC distribution. It enables precise and reliable estimates of current carbon stocks, which is an essential tool for analyzing and modeling the effects of various factors on soil OC sequestration potential. However, it must be noted that soil carbon levels rely heavily on the primary long-term factors related to soil formation, such as soil bulk density or soil classification. These attributes can be strongly influenced – degraded or improved – by changes in soil use and management practices. Thus, the implementation of thorough laboratory analyses, regular data updates, and observation of its evolution are vital. In terms of the broader implications of these findings, understanding the potential for soil to sequester carbon has far-reaching impacts on the ability to mitigate the effects of climate change. Soil sequestration of CO_2 plays a significant role in reducing greenhouse gas emissions, a leading cause of global warming. The insights from this study offer a valuable contribution toward global efforts to offset carbon emissions and promote more sustainable land use practices. To counteract the effects of climate change, enhancing the capacity of the soil to act as carbon sink is a key strategy that demands ongoing research and attention.

Disclosure statement

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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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