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# Soil carbon storage and retention: a critical synthesis on concepts, research opportunities and sustainable application in environmental engineering

## Armazenamento e retenção de carbono no solo: síntese crítica de conceitos, oportunidades de pesquisa e aplicação sustentável para engenharia ambiental

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## ABSTRACT

Soil functions have been threatened by anthropogenic activities, compromising ecosystem services and unbalancing the carbon biogeochemical cycle. Soil carbon sequestration (SCS) is an emergent solution for mitigating climate change and restoring degraded soils. Soil organic carbon (SOC) stock plays a relevant role in measuring ecosystem restoration projects. Nevertheless, the soil is complex and heterogeneous. It is subjected to the soil-plant-atmosphere system interaction and is controlled by many multidisciplinary processes in the C cycle, from C air sequestration to C soil retention. There are still a series of uncertainties around concepts, mechanisms and methodological protocols to assess SOC stock. Through a critical literature review, this paper aimed to synthesize concepts with a cross-disciplinary approach, to analyze research opportunities and to examine sustainable applications in light of environmental engineering. The results point out the conceptual advances in organic matter stabilization in soil and highlight the research gap on the dynamics of the SOC and soil water flux within structured soil profiles, which may be explained using geotechnical engineering concepts. We also observed the need for a multidisciplinary framework of variables that is able to clarify the transdisciplinary contributions to this field. Finally, the SOC stock is an index that may be employed as an indicator of ecosystem restoration results in C-based engineering solutions.

**Keywords:** carbon sequestration mechanisms; soil organic matter stabilization; soil hydrodynamics; ecosystem restoration; geotechnics.

## RESUMO

As funções do solo têm sido ameaçadas pelas atividades antrópicas, comprometendo a provisão de serviços ecossistêmicos e desiquilibrando o ciclo biogeoquímico do carbono. O sequestro de carbono no solo é uma solução para a restauração de solo degradado e para a mitigação climática. O estoque de carbono orgânico do solo (C-estoque) é um indicador que orienta projetos de restauração de ecossistemas e verifica resultados. No entanto, o solo é um sistema complexo e heterogêneo, sujeito às interações do sistema solo-planta-atmosfera, e é controlado por uma série de processos multidisciplinares que envolvem desde a captura de C da atmosfera até a retenção de C no solo. Ainda, há uma série de incertezas sobre conceitos, mecanismos de retenção e protocolos de mensuração do C-estoque. Por meio de uma revisão crítica da literatura, este artigo teve o objetivo de sintetizar conceitos com uma abordagem interdisciplinar, analisar oportunidades de pesquisa e avaliar aplicações sustentáveis à luz da engenharia ambiental. Os resultados apontam avanços conceituais na temática de estabilização da matéria orgânica no solo e ressaltam oportunidades de pesquisa sobre a dinâmica entre o carbono orgânico e o fluxo de água dentro de perfis de solo estruturados, o que pode ser compreendido por meio de conceitos da engenharia geotécnica. A revisão ainda sinaliza a ausência de um enquadramento multidisciplinar das variáveis que delimite a análise transdisciplinar do tema. Por fim, o C-estoque é um índice que pode ser utilizado em soluções de engenharia baseadas em C como um indicador dos resultados de restauração ecossistêmica.

**Palavras-chave:** mecanismos de sequestro de carbono; estabilização da matéria orgânica no solo; hidrodinâmica do solo; restauração de ecossistema; geotecnia.

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## Introduction

The impact of anthropogenic activities on the environment is an urgent issue in science. Damage to ecosystems and greenhouse gas emissions (GHG) have a detrimental effect on the balance of biogeochemical cycles (IPCC, 2023). An agreed parameter for monitoring this issue is the concentration of carbon dioxide ($CO_2$) in the atmosphere (Friedlingstein et al., 2020).

Besides the atmosphere, carbon in the planet is divided into four other pools: oceanic, geologic, biotic and pedologic. The carbon depletion caused by land use changes in the latest pool (soil) is a relevant factor in the increase of carbon concentration in the atmosphere (Lal et al., 2015). As a solution, strategies of soil carbon sequestration (SCS) contribute to soil carbon storage, which has multiple benefits on ecosystem restoration and climate mitigation (Granja Dorilêo Leite et al., 2025; Xiao et al., 2025).

The soil pool comprises soil organic carbon (SOC), of the order of 1.550 x $10^{15}$ g (or Pg) C, and soil inorganic carbon (SIC), of circa 950 Pg C, up to 1 m depth (Batjes, 1996; Lal, 2008). As put forward by Sharififar et al. (2023), SIC occurs as primary carbonates derived from lithogenic processes (geogenic—alteration of primary carbonate; and biogenic—accumulation of residues of animals and plants) or secondary carbonates (pedogenic—formed on site as a result of the recrystallization of pre-existing carbonates). SIC is also found in solutions as dissolved ions (DIC). Precipitation of carbonate requires the availability of $Ca^{2+}$ or $Mg^{2+}$ ions and $CO_2$ in the soil. Because of the long turnover time of SIC sequestration, it has been overlooked. Nevertheless, SIC has recently gained attention for its potential for carbon storage, especially in arid regions (Dina Ebouel et al., 2024). On the other hand, SOC is formed through the deposition-decomposition of organic matter (OM) (Muhammad et al., 2025). This is a resource for soil biota and has low density and high reactivity. The SOC pool is extremely dynamic; gains and losses of SOC can be expressed through a balance between biomass-C inputs, or I (natural or managed aboveground biomass, root C and exudates and C sediments) and outputs or losses, or L (oxidation, mineralization, erosion and leaching). Part of SOC can be easily removed, while part of it may stabilize for a long time along the soil profile (3,000 Pg C below 1 m) (Köchy et al., 2015). If, in a period, I>L, an accrual of SOC indicates SCS (Lal et al., 2015).

C sequestration was previously defined as the uptake of a C substance from one reservoir to another pool (IPCC, 2001). According to FAO (2019), in the lens of soil, carbon sequestration *"corresponds to an increase in the stock of soil carbon that can be measured or estimated in different ways from balances of carbon fluxes"*. Despite the relevance of SIC in the carbon cycle, SCS has been focused only on SOC stock (expressed as Mg SOC $ha^{-1}$ at a given soil depth and restricted to the fraction <2 mm). Recently, Don et al. (2024) proposed the following definition for SCS: "*the process of transferring C from the atmosphere into the soil through plants or other organisms, which is retained as SOC, resulting in a global C stock increase in the soil*". It has to be noted that SOC storage and stock have the same meaning, while SOC accrual is the difference between the initial and SOC stock in a unit area in a period that characterizes SCS. On the other hand, SOC content is the amount of carbon in a soil sample relative to the total mineral content (expressed in percentage of mass), and SOC retention concerns the stabilization of SOC stock over time.

SCS became a financial product to stimulate sustainable land management. Carbon credits can be traded if quantified and monitored (Dupla et al., 2024). Nonetheless, inventories of SOC stock hold uncertainties, and there is a lack of knowledge on SOC dynamics and an absence of consensus on methods of measuring and monitoring soil-based strategies (Paustian et al., 2016). In addition, soil has an interdisciplinary nature (Brevik et al., 2015). It is complex, heterogeneous and dynamic, dependent on anthropogenic perturbance and climate conditions (Mitchell and Soga, 2005).

In this context, comprehension of SOC dynamics requires the integration of different areas of knowledge. Only a multidisciplinary framework may allow advances in research through disciplinary connections and cooperation among teams. This literature review aims to identify the recurrent research themes linked to SOC dynamics, synthesize the most significant conceptual contributions and analyze research opportunities and sustainable application through the lens of environmental engineering.

To do so, the literature review followed the methodology proposed by Boell and Cecez-Kecmanovic (2014) based on a multidisciplinary search framework starting from the carbon biogeochemical cycle (soil-plant-atmosphere) and constrained by soil properties and structure, soil organic carbon dynamics and soil organic carbon stock. Environmental engineering aspects delimited research on sustainable application. References were obtained in web-based bibliographic databases such as the Brazilian Portal of Scientific Journals (CAPES Periódicos), Google Scholar, ScienceDirect and Scopus.

## Concepts and Definitions

### Soil as an ecosystem

Soil is a complex, particulate, multiphase system in which the solid phase forms a matrix or skeleton containing interconnected or not connected pores (Figure 1). The solid matrix is composed of primary minerals, which are those inherited from the weathered parent rock (typically, siliceous minerals such as quartz, feldspar, and mica); noncrystalline or amorphous solids, which are silica-rich mineral-like solids such as obsidian, opal, geyserite, and biogenic silica); secondary minerals such as those called clay minerals, originating from bio-physical-chemical weathering of primary minerals (belonging to the families of kaolinite, illite, and montmorillonite); oxides and hydroxides (comprising bonding elements to primary minerals and amorphous solids, typically originating from leaching of iron and aluminum from upper soil layers); and OM (typically labile and recalcitrant plant litter residues).

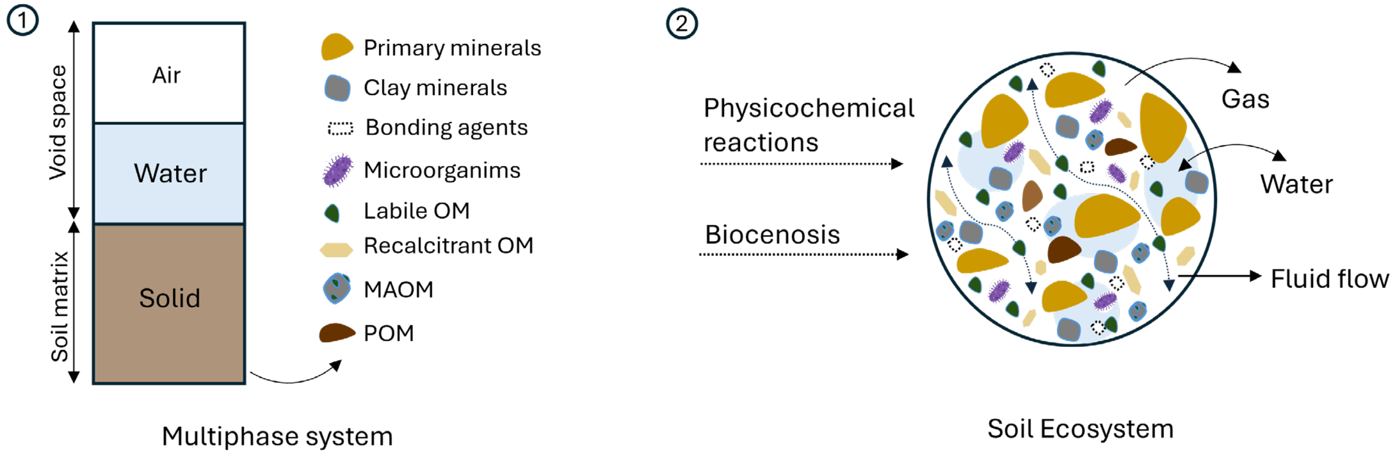

**Figure 1 – The soil multiphase ecosystem. (1) Distinct phases encountered in the soil structure are delimited by the pore spaces and the solid matrix in which the solid phase exceeds mineral particles. (2) The physicochemical weathering reactions and bioactivity affect the interaction among soil solids in the presence of air and water in the pore spaces. This combination of phases, reactions and living organisms turns the soil into an ecosystem.**

Soil pores can be filled by fluids such as gases (originating from the atmosphere and/or resulting from microorganisms' action) and/or water (containing dissolved electrolytes and organic and/or inorganic substances, dissolved or in the form of colloids).

Soil structure, as herein considered, includes a combination of the soil matrix arrangement, comprising the distribution, size and interconnections of the solid particles; pores arrangement, which includes the distribution, size and interconnections of the void's spaces, and interaction effects among the solids of the matrix and the fluids within the pores (essentially, water), which may change over time particularly due to human interferences. Furthermore, the soil is home to billions of organisms responsible for biocenosis, a term that better represents the soil community (Primavesi, 2018).

From the viewpoint of environmental engineering, the grain size of the particles (ϕ) composing the soil matrix constitutes a divisor to be considered as, in most cases, individual particles of size greater than sand (ϕ>0.075 mm), typically encompassing primary minerals, do not show any relevant aspect related to carbon storage or retention (CS/R). On the other hand, particles comprising the fine soil fraction (silt fraction, ϕ ranging from 0.075 to 0.002 mm, and clay fraction, with ϕ<0.002 mm), play a relevant role in CS/R, either acting individually or in the form of clusters or aggregates (American Society for Testing and Materials—ASTM, 2025).

Soil clusters comprise an assemblage of interconnected fine soil particles with complex aggregation formation. According to Bronick and Lal (2005), aggregates result from the rearrangement, flocculation, and cementation of mineral particles with organic and inorganic substances. The hierarchical aggregation dynamic is based on the attachment of bonding agents (organic molecules, clay, and polyvalent cations) to form micro-aggregates (<250 µm), which progressively join other particles to form macroaggregates (>250 µm). A discussion on cluster formation, including the presence of OC input, is provided by Denef et al. (2002). The experimental results put forward by these authors indicated that fine fraction soil mineralogy has an important role in soil cluster formation in the presence of OC.

It is interesting to note here that such mineralogy is directly related to the specific surface area (SSA) of clay minerals, defined as the area of the surface of the particle divided by its mass or volume (Table 1). The SSA of clay minerals comprises a good indicator of their potential to store or retain, besides water, organic or inorganic substances in their diffused or double layer (Mitchell and Soga, 2005). This double layer is inherent to a clay mineral which presents unbalanced negative electric charges on its surface and positive electric charges at its corners. To balance that, based on their cation exchange capacity (CEC), cations and anions are attracted to the clay surface including polarized water molecules, which is limited by the hydrated interlayer surface (basal space). Thus, dissolved organic matter (DOM) can be adsorbed in the clay mineral double layer (Six, 2002; Kleber et al., 2015).

It is also interesting to note that DOM can be transported with water as it flows through the pores of the soil, either as a result of rain-water infiltration in an unsaturated soil profile or through water percolation in the saturated soil below the local water table. The degree of soil saturation (S) is defined by the ratio between its void ratio and its total volume. If the soil is saturated, S=1. Saturated and unsaturated water flow rates in soils strongly depend on hydraulic soil properties, which are highly dependent on the soil structure (Fredlund et al., 2012).

**Table 1 – Clay mineral properties.**

| Mineral | SSA ($m^2\ g^{-1}$) | CEC ($cmol\ kg^{-1}$) | Basal space (Å) |
|---|---|---|---|
| Kaolinite | 7–30 | 3–15 | 7.2 |
| Illite | 65–100 | 10–40 | 10.0 |
| Montmorillonite | 50–840 | 80–150 | 9.6 |

Source: Grim (1968) and Mitchell and Soga (2005).

## Soil organic carbon storage

SOC is a result of the soil organic matter (SOM). It is continuously changing, varying in depth and space and it is dependent on the broken-down plant metabolism, which is regulated by bioactivity and water (Lal, 2004b). SOC storage and retention depend on the deposition and degradation of OM and its interactions with the soil matrix. Thus, a comprehensible understanding of SOM is necessary to assess SOC dynamics (Cotrufo et al., 2019).

### *Soil organic matter*

As put forward by Tan (2003), SOM is derived from the deposition of residues of plant inputs or animals into the soil. Bio-physical-chemical transformation converts this dead material into organic compounds at various degrees of decomposition. On the surface, it is called litter. Downwards, it is broken down into simple molecules (e.g. monomeric sugars, amino acids), polymeric molecules (e.g. cellulose, lignin, and protein), and a highly stable black-brown substance called humic substances. Such substances comprise a mixture of amorphous, polydisperse organic colloids with electrochemical properties such as those associated with clay minerals (e.g. adsorption).

SOM has a diversity of physical forms and molecular structures that can be identified by its biological stability, decomposition rate and turnover time. This allows a better understanding of the OM dynamics in soils (Prescott & Vesterdal, 2021). Most of the SOM is found in two fractions (Lavallee et al., 2019; Leuthold et al., 2022): a lower density (<1.6 to 1.85 $g/cm^3$) and larger size (>53 µm) particulate organic matter (POM) and a higher density (>1.85) and smaller size (<53 µm) mineral-associated organic matter (MAOM). These fractions hold different physical and chemical properties, persistence and vulnerability to land use changes. POM is largely composed of plant-derived matter found in the organic soil horizons (horizons O and A) and of rhizosphere fragmentation, which are partially decomposed/depolymerized and insoluble. It may be physically protected against degradation by occlusion within aggregates. On the other hand, MAOM is mostly formed by thermolabile compounds of microbial origin in the form of microscope molecules of OM leached directly from litter or chemically transformed by soil fauna associated with mineral surfaces by adsorption (Figure 2).

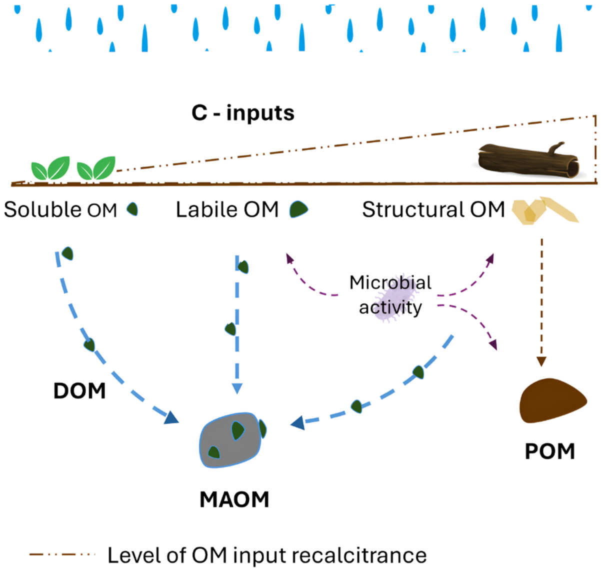

**Figure 2 – Transformation pathways of soil organic matter fractions. The organic matter (OM) placed on the soil surface presents molecular diversity structures and different levels of recalcitrance. Bio-physical-chemical transformation also begins at the surface level and OM has already entered soils with distinct biological stability and electrochemical properties. Dissolved organic matter, particulate organic matter and mineral-associated organic matter may be formed and encountered along the profile.**

Despite the large proportion of POM and MAOM in soils, a third fraction of the OM, the DOM, is considered the mobile fraction. It is responsible for the C transport through soil water; it is highly reactive and plays a critical role in C-stabilization as it may reach almost all soil compartments by advection and diffusion (von Lützow et al., 2007). This fraction may also contribute to aggregation and the formation of MAOM under adsorption mechanisms (e.g. Gmach et al., 2020).

## Soil organic matter retention

Part of the C input in the soil is mineralized, and part remains stabilized for different mean residence time (Lal et al., 2015). SOM stabilization mechanisms protect organic molecules against mineralization and oxidation. The two main physical protection mechanisms occur through organo-mineral association and aggregation (Figure 3) (Six, 2002; Lützow et al., 2006; Schmidt et al., 2011).

The mineral association mechanism is an interaction between OM and the mineral surface and metal ions (Lützow et al., 2006). MAOM refers to OM encapsulated in micropores or micro-aggregates in the soil matrix directly associated with the mineral surface (organo-mineral) or through organo-organic and organo-metal-oxide interactions (Possinger et al., 2020). These associations are regulated by multimode sorption mechanisms and by coprecipitation (Kleber et al., 2015). They are controlled by three key elements: aqueous species (DOM), microbial metabolism and clay mineral surface (Dwivedi et al., 2019). In this sense, organo-mineral interactions may be constrained by the percentage of fine particles in soil (<2 µm), setting a soil carbon saturation potential (Hassink, 1997).

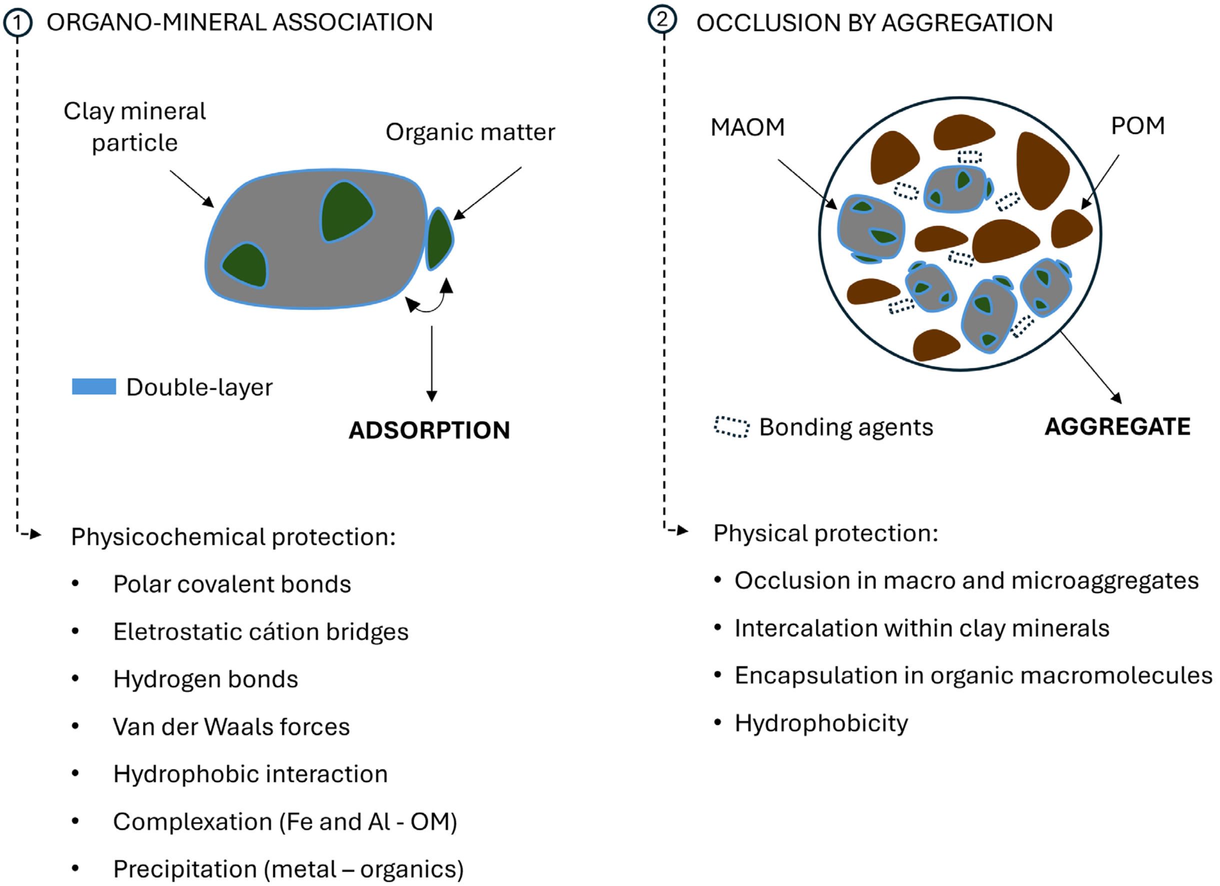

**Figure 3 – Soil organic carbon (SOC) protection mechanisms. (1) Process of organic matter association with the clay mineral particle through the adsorption that occurs in the hydration interlayer. (2) Protection of the SOC through the occlusion into the aggregates. Physicochemical and physical interacting processes were compiled based on Mitchell and Soga (2005), Lützow et al. (2006) and Kleber et al. (2015).**

OM sorbed in clay particles may partially or fully cover their SSA, modifying its C-saturation capacity (Kaiser and Guggenberger, 2003). As put forward by Six et al. (2024), the maximum C stabilization in 2:1 clay-dominated soils may be ~ 42 % higher than the stabilization in 1:1 clay-dominated soils.

Physical aggregation consists of the occlusion of OM compounds via micro-aggregation within macroaggregates (clusters) and intra-aggregates (Bronick and Lal, 2005). Aggregation restricts the decomposition of OM by microbes and fauna. Molecular C compounds stay spatially isolated (Six, 2002). SOM is the primary binding agent for aggregation, and POM can also act as a nucleus for macro-aggregation, which results in an arrangement of low-density POM fragments protected by intra-aggregation (Lavallee et al., 2019). Occlusion processes are also guided by organo-mineral interactions as a prior process of aggregation (Lehmann et al., 2007).

In this context, the occurrence of stabilization mechanisms depends on the soil structure in each horizon, as well as on the chemical structure of organic molecules. The complexity of clarifying SOM stabilization stems from the simultaneous occurrence of variable mechanisms (Lützow et al., 2006).

## Soil organic carbon stock

Soil carbon stock involves SOC and SIC. Although SIC represents a significant portion of C in some types of soil, it is considered a static pool and is excluded from SCS strategy measurements (FAO, 2019). Considering the bulk density of the soil at a given depth, the SOC stock can be evaluated through Equation 1. Usually, it is measured in one layer or multi-layers to 30 cm depth.

$$SOC_i\ stock = OC_i\ x\ BD_i\ x\ (1 - G_i)\ x\ t_i\ x\ 0{,}1 \qquad (1)$$

Where:

$SOC_i$: the SOC stock of the soil layer (Mg C ha$^{-1}$);
$OC_i$: the SOC content of the fine fraction in the layer (g kg$^{-1}$);
$BD_i$: the bulk density of the soil sample (g cm$^{-3}$);

$G_i$: the percentage of coarse particles of the layer (g $g^{-1}$);
$t_i$: the thickness of the layer (cm);
0.1: a unit converter factor.

POM and MAOM fractions have also been used, separately, in the evaluation of SOC stocks (e.g. Souza Medeiros et al., 2022).

Different methodologies and assessment protocols can be employed to obtain the SOC stock parameters, leading to largely differing results (e.g. Poeplau et al., 2017; Dupla et al., 2024). For example, Poeplau et al. (2020) showed that comparison results between a default modelling reference of SOC stock and in situ measurements may be overestimated by 71% in depleted soils and underestimated by 549% in carbon-rich soils. Despite uncertainties of modelling results, the adoption of remote sensing technologies, such as spectroscopy imaging (hyperspectral), has promised effectiveness in SOC prediction (e.g., Guo et al., 2021; Roy et al., 2024).

Finally, Bispo et al. (2017) state that the use of international standards may contribute to improving the reliability of the measure, report and verification (MRV) protocols on soil C quantification, mainly when it is applied to the carbon market

## Soil Storage and Retention

Research into soil carbon dynamics highlights the concept of soil as a multiphase ecosystem that contains biotic and abiotic compounds. Even though soil structure (e.g., skeleton, pore-distribution, mineralogy) regulates the transport, storage and retention of water, gas and OM, most of the interactions in the processes and mechanisms of carbon storage and retention require bioproducts (Figure 4).

Additionally, SCS science goes beyond the boundaries of a single scientific area or a specific problem statement. It embraces several research areas such as environmental, soil and plant science, microbiology, atmosphere, and hydrology, among others (Possinger et al., 2020; Verma and Ghosh, 2024) with a myriad of research questions concerning, for instance, food security, climate mitigation, and soil and ecosystem restoration. Moreover, it is a relatively young area of knowledge (Dina Ebouel et al., 2024). Since there is no specified research framework for each science area, interconnected knowledge is needed to investigate any individual phenomenon on soil C storage and retention. It comprises divergences in vocabulary and concept description (Don et al., 2024), as well as in measurement standards and quantification methods, which are further applied to carbon credit protocols (Dupla et al., 2024).

In this context, concepts on soil C storage and retention can be synthesized through the lens of carbon pools (atmospheric-biotic-pedologic) to provide an overview of concepts and mechanisms associated with soil C and their research boundary areas (refer to Table 2).

## Soil carbon in the pedosphere profile

Previous studies on SOC have considered that SOC occurs in the first meter of the soil profile (e.g. Jobbágy and Jackson, 2000).

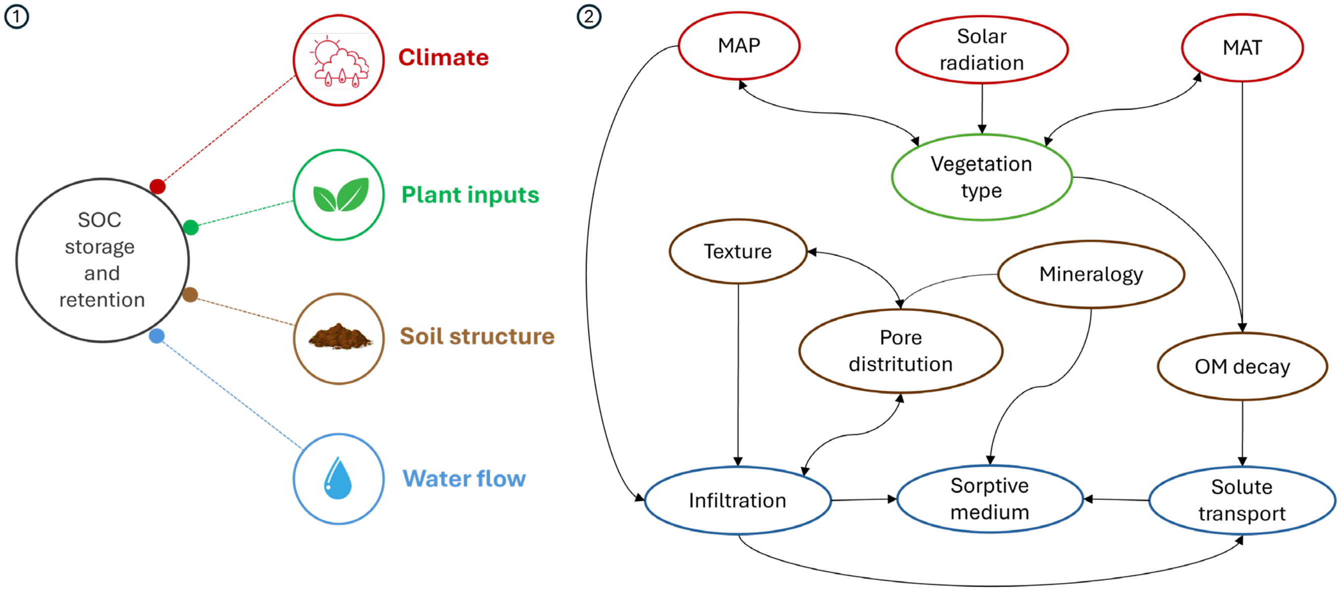

**Figure 4 – Soil organic carbon (SOC) influencing factors and interactions between variables. (1) The formation and stabilization of SOC encompasses elements from the atmosphere, biota and pedosphere and depends on the water dynamics within the soil. (2) In this sense, several phenomena occur simultaneously, with the interaction among variables resulting in complex cause-and-effect relationships. The picture also illustrates multidisciplinarity in the field.**

**Table 2 – Soil organic carbon storage and retention: overview of concepts and mechanisms by carbon pool.**

| Carbon pool | Thematic | Key factors | References |
|---|---|---|---|
| Atmospheric | MAP and MAT | Wet and dry cycles | Kramer and Chadwick, 2018; Heckman et al., 2023; Galluzzi et al., 2024 |
| | Climate change | Warming | Rocci et al., 2021; Georgiou et al., 2024; Wang et al., 2024; Wei et al., 2024 |
| Biotic | SOM input | Vegetation input | Cotrufo et al., 2022; Paltineanu et al., 2024; Sun et al., 2024 |
| | | Roots metabolism | Gross and Harrison, 2019; Dijkstra et al., 2021 |
| Pedologic | Soil structure | Physical-chemical properties | Luo and Viscarra-Rossel, 2020; Luo et al., 2021; Fukumasu et al., 2022; |
| | | Hydrodynamic | Lal, 2020; Védère et al., 2022 |
| | | C-saturation | Georgiou et al., 2022; Rodríguez-Albarracín et al., 2023; Six et al., 2024 |
| | SOC storage | SOM decay | Cotrufo et al., 2015; Lehmann and Kleber, 2015; Smith et al., 2018; Prescott and Vesterdal, 2021 |
| | | SOM fractions | Poeplau et al., 2018; Cotrufo et al., 2019; Lavallee et al., 2019; Angst et al., 2023 |
| | SOC retention | Stabilization concepts | Schmidt et al., 2011; Lehmann et al., 2020; Cotrufo and Lavallee, 2022 |
| | | Physical protection | Chi et al., 2022; Scartazza et al., 2023; van den Bergh et al., 2024 |
| | | Mineral association | Kleber et al., 2015; Hemingway et al., 2019; Kopittke et al., 2020; Possinger et al., 2020 |

MAP: mean annual precipitation; MAT: mean annual temperature; SOC: soil organic carbon; SOM: soil organic matter.

Thus, SOC stock quantification has been limited to 1 m of depth, with the majority of protocols admitting 30 cm of depth (FAO, 2019). This pattern depicts previous efforts on carbon sequestration strategies to evaluate C depletion and degradation in agricultural soils (Lal, 2004a).

Concerns in agronomy are related to the topsoil horizons, especially the organic (O) horizon, which is the basis of nutrient cycling and soil fertility for food security. Nonetheless, nowadays, soil C storage and retention issues have a broader application, for instance, to guide strategic measures and quantify climate mitigation and ecosystem restoration aspects (e.g. Krug et al., 2006; Mäkipää et al., 2024). Indeed, considering only topsoil layers might underestimate SOC stocks and storage and retention potential (Poeplau and Gregorich, 2022). SOC changes in depth under the influence of water flux conditions in the soil profile, vegetation and root zone. Microbial metabolism may also change deep horizons, inhibiting SOC mineralization (e.g. Olson et al., 2014). Furthermore, the thickness of soil profiles may exceed 30 m depth according to soil formation conditions (e.g. Huat et al., 2012). In particular, lateritic soils, which undergo leaching of $SiO_2$ and deposition of $Fe_2O_3$ and $Al_2O_3$, have a high potential for storage and retention of C in deeper soil layers (e.g. Grim, 1968; Rodríguez-Albarracín et al., 2023). Therefore, research efforts should focus on SIC and SOC surveys below the conventional 1 m depth, especially in tropical and subtropical regions. To do so, undisturbed sampling at depth is required, which can be achieved using, for instance, well-known geo-environmental sampling techniques such as the direct push method (e.g. ASTM, 2023) with fine wall thickness devices.

## Soil hydrodynamics on soil organic carbon mobility

The hydroclimatic regime influences soil C dynamics in multiple ways. As put forward by Védère et al. (2022) in the macroscale, mean annual precipitation (MAP) affects soil surface conditions, plant inputs, runoff and water infiltration and evapotranspiration (Figures 5A and 5B). In the soil profile, water flows and transports soluble matter and controls biological dynamics (SOM production). At the microscale, water influences soil C stabilization mechanisms (Figure 5C).

The dynamic movement of water may establish layers of saturated conditions with distinct decomposition rates and nutrient dynamics that affect several carbon stabilization and destabilization mechanisms (Yusuf et al., 2024). Moisture also drives differences in soil factors regulating MAOM concentration and persistence. It depicts a clear divergence in the total organic carbon retained in reactive minerals between types of soil (humid and arid soils) according to water balance (Heckman et al., 2023). Additionally, soil moisture regulates the leaching of OM and, in intermediate moisture conditions, the translocation of Ca-carbonate polymerization and the flocculation process of Fe-Al and colloids adsorption (Kramer and Chadwick, 2018).

SOM affects the field capacity (FC). As mentioned by Santos Brito et al. (2011) and Lal (2020), it increases water retention (WR); likewise, FC condition is favorable for bioactivity and SOM retention (Védère et al., 2022). Wet and dry cycles strongly affect soil properties and soil aggregate stability; therefore, the capacity of soil to physically protect OM (Jesús Melej et al., 2024). On the other hand, close to saturation conditions, water encounters flow paths in aggregated media according to aggregate roughness and size of pores, which settle preferential flows that by-pass the aggregate matrix (Carminati et al., 2008).

Water is in the center of the SOM formation, vertical distribution and retention in each soil structure. Water flows through soil-void spaces, transporting matter—ions and suspended solids—and interacts with clay minerals (e.g. Mitchell and Soga, 2005). Physical and bio-physical-chemical processes are involved in OM transport in soil and can control SOC stock (Figure 5). DOM transport is correlated to the soil hydraulic conductivity (K) and its retention to the type of minerals present in the soil.

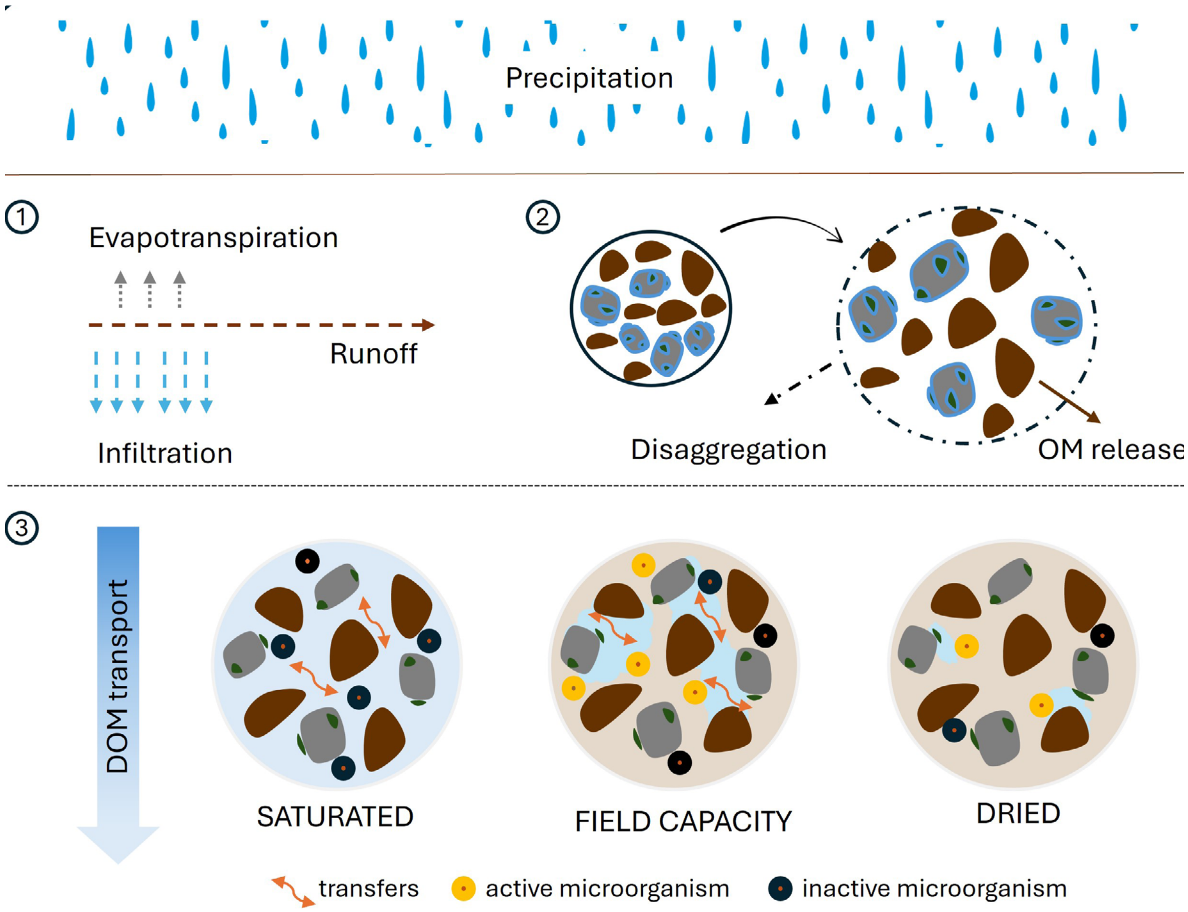

**Figure 5 – Water effect on soil organic matter (OM): (A) Precipitation generates horizontal (runoff) and vertical (infiltration) transport of particles and soluble OM depending on soil surface conditions (saturation and/or crust formation). Infiltration results in the leaching and integration of OM along the soil profile. Part of the water can be released as vapor. (B) Raindrops can induce aggregate destabilization. Detached OM may be transported by erosion and accumulated along the pathway. (C) Water content induces a gradient of soluble organic molecules, transfers of microorganisms and nutrients (advection and/or diffusion) and affects oxygen supply. Microbial-substrate accessibility (biodegradation) performs mineralization or stabilization of OM according to the degree of saturation.**

Researchers have observed the complexity of examining soil C mobility in soil profiles. For instance, Fukumasu et al. (2024) mention the influence of aggregation aspects on SOC transport, and Si et al. (2018) observed the relationship between DOC vertical movement, soil sorptive capability and sorption/desorption dynamics with SOC allocation along the soil profile. Considering agricultural practices, Jephita et al. (2023) attempt to correlate hydrodynamic parameters such as the saturated hydraulic conductivity (Ks), steady state infiltration rates (is) and soil sorptivities (Sp) with soil parameters such as bulk density (BD), SOC content and aggregate stability. Indeed, there is a consensus on the lack of information on correlating soil hydrodynamic-SOM transport and C retention in the subsoil (Falloon et al., 2011; Sun and Mu, 2022; Yu et al., 2023).

Despite progress in descriptions of hydrological processes in numerical simulations, knowledge is still required of hydrological parameters and solute migration in the context of organic carbon. Hydraulic conductivity, degree of saturation, fluid temperature and viscosity are some of the hydrodynamic soil parameters that require further investigation in response to SCS. In addition, responses of soil C stabilization dynamics may be correlated to soil-water retention curves (Fredlund et al., 2012), which comprise a sort of soil DNA (Ibañez, 2008). Moreover, the migration of ions in soil water that are controlled by advection, molecular diffusion and mechanical dispersion (Figure 6) is subject to its capacitance (Mitchell and Soga, 2005). All these aspects may strongly affect SOC vertical distribution and stabilization mechanisms. To overcome the complexity of such interactions, numerical programs like Hydrus-1D, which allow simulating water flux and solute transport in variably saturated media, may be useful to the comprehension of the SOC-water dynamics (e.g. Biesek et al., 2024).

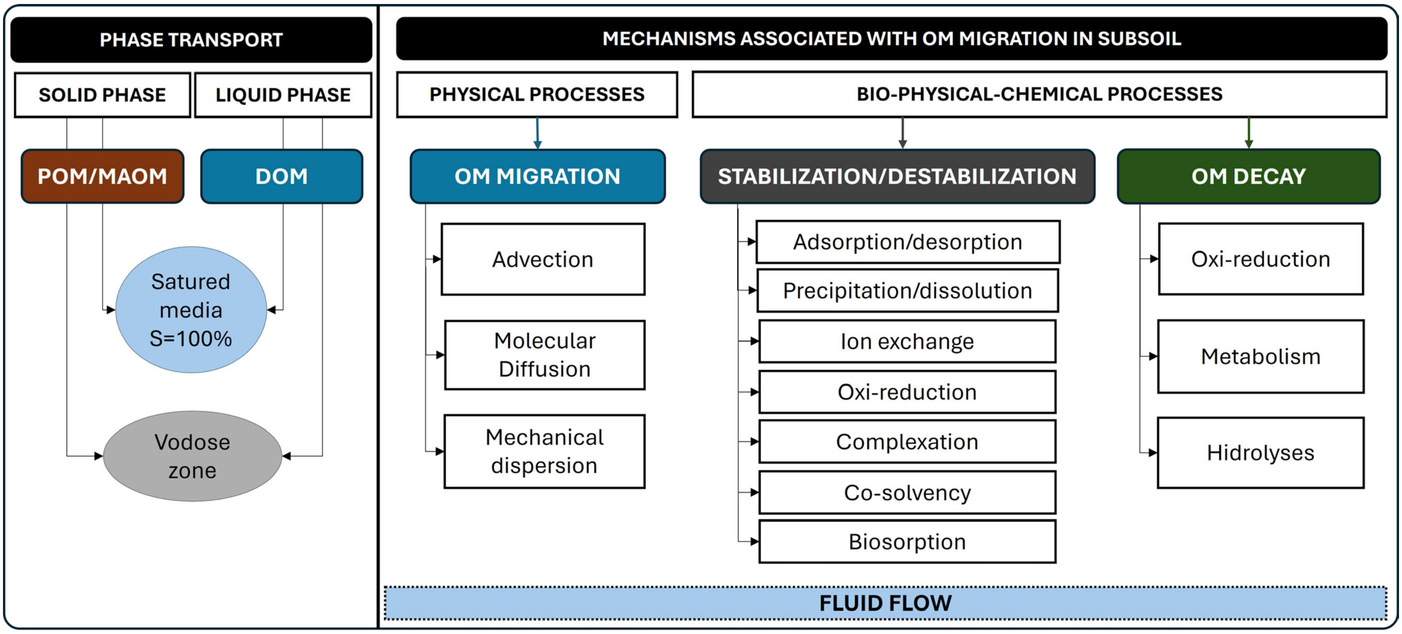

**Figure 6 – Organic matter phase of transport and mechanisms of migration in the subsoil.**

## Soil assessment and soil organic carbon stock

Soil multifunctionality supports planet life, provides food, water, and energy, protects biodiversity and mitigates climate (Kopittke et al., 2022). Soil degradation caused by land-use change, industrialization and urbanization raised concerns about the preservation and restoration of soil functions and services in a holistic view beyond previous concerns only referring to food security (Bünemann et al., 2018). In this context, evaluating SOC losses and storage potential becomes crucial to establishing recovery strategies.

Soil quality index (SQI) (e.g. Guo et al., 2024), soil security (SS) multidimensional concept (e.g. Evangelista et al., 2023) and soil ecosystem services (SES) (e.g. Latawiec et al., 2022) are some of the relevant frameworks employed to evaluate vital soil functions and services.

SQI encompasses soil properties and soil functions, being related to its capacity to perform the ecosystem functions to sustain life and environmental balance (Bünemann et al., 2018). However, the physical, chemical and biological attributes of soil selected for SQI are not standardized (Raiesi, 2017; Li et al., 2023), and links between soil quality and soil socio-ecological functions are not well-established (Guo et al., 2024).

On the other hand, the multidimensional concept of SS consists of five soil dimensions: capability, condition, capital, connectivity and codification—that can be understood, quantified and managed through soil functions, services and threats (McBratney et al., 2014). A proposed SS assessment framework based on soil functions (properties and processes) is being discussed (Evangelista et al., 2024). Moreover, SES also falls into four service categories: provisional, regulatory, cultural and supporting (Baer and Birgé, 2018). It is derived from the concept of ecosystem services (ES), which are the direct or indirect benefits that ecosystems provide to people (MEA, 2003). SES is directly linked to sustainability. The type, quantity and quality of SES depend on edaphic properties and soil functions. The valuation of SES is linked to natural features and land management (Pereira et al., 2018).

Besides this framework assessment, other efforts have been made to link soil structural properties to soil functions (e.g. Rabot et al., 2018; Orlova and Savin, 2024; Séré et al., 2024). However, the lack of clear interpretation schemes has limited opportunities to support decision-makers and public policies (Bünemann et al., 2018; Rodrigues et al., 2021) as well as constrained the quantification of functions and services for monetary valuation (Baveye et al., 2016).

Notwithstanding, SOC stock is an indicator that exhibits soil functions and quality (Kopittke et al., 2022). Indeed, SOC has been taken as a planetary resource to support ES (Lorenz et al., 2019) and has been used to boost comprehension of changes in the soil surface and subsurface under degradation (Blanco-Canqui, 2024; De Laurentiis et al., 2024; Kavukattu Sreekumar et al., 2024). In addition, advances in new technologies such as the hybrid modeling approach and machine learning have enhanced the SOC prediction to support restoration management practices (Ding et al., 2025). However, further investigation is needed to correlate SOC stock to SES.

Moreover, an indicator based on the organic carbon-to-clay ratio (SOC:Clay) has been admitted to specify levels of soil structural degradation (Dexter et al., 2008; Johannes et al., 2017; Prout et al., 2021).

However, owing to the variability of soil types, there are uncertainties on threshold values to adopt SOC:Clay on a large scale (Feeney et al., 2024; Mäkipää et al., 2024).

Despite the “in progress” development of accurate methods to quantify SOC stock, SOC represents a reliable index to express soil multifunctionalities and services. Indeed, it is guiding national and global public policies on soil restoration (FAO, 2019; IPCC, 2019; European Commission, 2023).

## Sustainable Applications

Environmental engineering provides solutions for environmental sanitation—delivery of proper disposal of wastewater and solid waste, drainage of rural and urban areas and control of water, soil and atmospheric pollution—considering the socio-environmental impacts of these solutions (Davis and Cornwell, 1991). Most environmental technologies are based on soil functions or aim to recover it. To ensure the provision of ecosystem services and increase multiple soil functions, mainly in degraded urban areas, technical and conceptual solutions such as climate-smart soils (Paustian et al., 2016), manufactured soils or technosols (Deeb et al., 2020), sustainable remediation (Ridsdale & Noble, 2016), carbon footprint calculation (Cappuyns, 2024) and incorporation of ES in the remediation process for contaminated sites (Harwell et al., 2021) have been considered. In most cases, SOC stock has been used as an indicator of ecosystem restoration (Sims et al., 2020).

For instance, Chen et al. (2021) applied SOC stock in two types of restoration strategies. The study pointed out that the two rehabilitated sites had different development trajectories for SOC sequestration and different performances of ecosystem carbon sequestration. Bucka et al. (2024) utilized total organic carbon to assess soil function deliverables in manufactured soil (rock mining waste and soil). The authors observed the potential of the waste and soil mixture to enhance carbon storage due to the abundance of OC-free mineral surfaces. In this case, besides recycling mining waste, the manufactured soil enhances SCS. Thus, restoration strategy choices may define future ecosystem performance.

In addition, changes in urban soil may promote soil degradation and loss of its functions (Pouyat et al., 2002). Reintegrating the ability of an area to absorb carbon from the atmosphere and store it in the form of SOC is crucial for air purification, climate regulation, runoff reduction and the development of sustainable cities (O’Riordan et al., 2021).

In this context, as illustrated in Figure 7, civil and environmental engineering solutions can employ SOC stock as a metric to express the ecological performance of a rehabilitated or constructed site. It may also be an opportunity to monetize the SCS as carbon credits if the challenges of policy integration for carbon markets, such as differences in the use of methodologies and protocols and the definition of the minimum monitoring period, are overcome (Batjes et al., 2024).

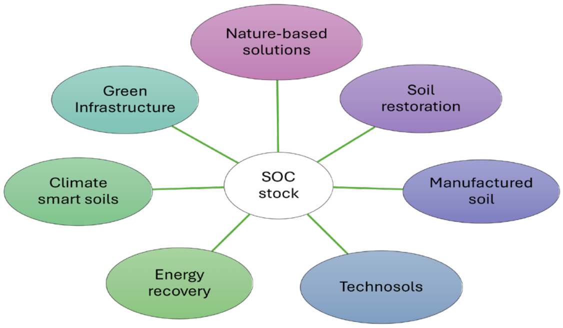

**Figure 7 – Soil organic carbon (SOC) storage and retention: C-based engineering applications. The SOC stock indicator may be used to monitor advances in soil restoration and also express the potential of the project to mitigate climate and restore ecosystem services.**

## Conclusion

Research on SOC sequestration has been advanced, driven by climate mitigation and soil restoration. Nevertheless, as soil carbon dynamics is a multidisciplinary science, it requires a transdisciplinary analysis considering the interaction of biophysical-chemical variables derived from the carbon pools (atmospheric-biotic-pedologic), which vary according to soil structure—water dynamics. This in turn requires a standardization of definitions, concepts and protocols. A guiding multidisciplinary framework of biophysical-chemical variables correlations would overcome the challenges related to SOC transdisciplinary research.

In addition, research opportunities dwell on data acquisition of SOC and SIC in soil profile, mainly in tropical and subtropical areas where water flux may potentialize SOC storage and retention in depth. Other aspects to be investigated through the lens of environmental engineering include the behavior of SOC storage and retention under the effects of soil hydrodynamics considering hydraulic conductivity, degree of saturation and soil-water retention curve.

The emergency to ecosystem restoration and climate regulation highlights the role of SOC stock as an index that reflects the integral capacity of the land to provide ecosystem services. Despite discrepancies in MRV protocols, the additionality of SOC in restored soils may generate soil carbon credits for a monetary carbon market.

Advances in SOC storage and retention research will contribute to minimizing discrepancies in MRV protocols. In this sense, the development of decision-support systems integrating SOC, hydrology and land-use data would be useful to endorse the elaboration of public policies to incentivize the restoration of degraded areas other than agricultural ones. For instance, restoring degraded soils in urban areas, rehabilitating green spaces and building nature-based solutions and green infrastructure through C-based engineering solutions.

## Authors' Contributions

**Antunes**, M. C.: conceptualization; data curation; formal analysis; investigation; methodology; writing — original draft; writing — review & editing; **Campos,** T. M. P.: formal analysis; funding; acquisition; project administration; supervision; validation; writing — original draft; **Araruna Júnior**, J. T.: data curation; supervision; validation; writing — review & editing.

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