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Formation pathways, ecosystem functions, and the impacts of land use and environmental stressors on soil aggregates

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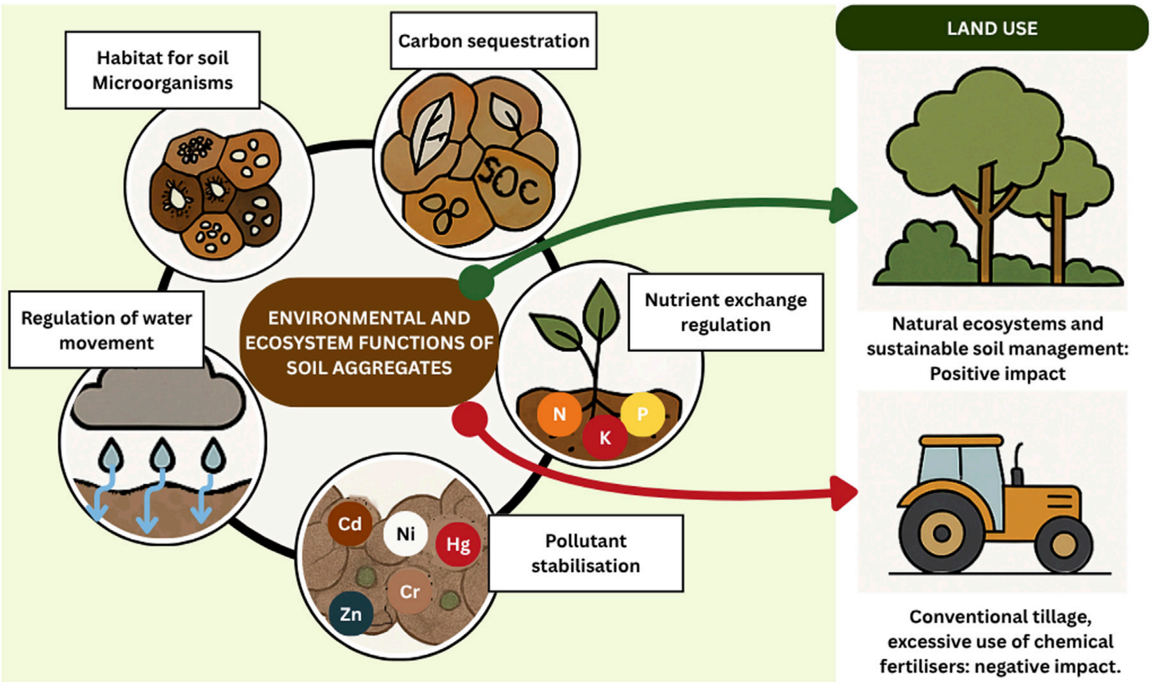
Soil aggregates have been identified as a critical biogeochemical indicator of soil health, playing a pivotal role in addressing numerous environmental challenges and maintaining ecological equilibrium within soil environments. However, there is a paucity of scientific literature that have provided a comprehensive understanding of the role of soil aggregates in the environmental and ecosystem functions of soils. The objective of this review article therefore is to provide a comprehensive overview of the environmental and ecosystem functions of soil aggregates. Subsequently, the effects of land use and/or changes in land use in the delivery of these functions were examined. It is established that soil aggregates play a pivotal role in five environmental and ecosystem functions within the soil, including: (i) the provision of habitat for soil microorganisms by regulating niche formation and predation; (ii) the long-term sequestration of soil organic carbon (SOC) within microaggregates, preserved in macroaggregates; (iii) the regulation of nutrient exchange at the soil–plant–water–atmosphere interface; (iv) the immobilisation of pollutants such heavy metal; and (v) the regulation of water movement in the soil. Land use has a major influence on the ability of soil aggregates to deliver these functions. The restoration of natural ecosystems (forests, grasslands, wetlands) has an overall positive effect, while farming, on the other hand, has a negative effect. Nevertheless, adopting sustainable management practices such as agroforestry, the use of organic soil amendments and reduced or no tillage can significantly reduce the adverse effects observed. Future research should look into how soil aggregates help capture carbon dioxide in dry areas through the inorganic carbon pathway and work on creating large-scale models to observe how these aggregates change and their effects on the environment and ecology.

KEYWORDS

soil carbon sequestration, climate change mitigation, arable land, soil health, clay mineralogy



GRAPHICAL ABSTRACT

1 Introduction

The complex interaction between land use and soil health has become a significant concern in contemporary agricultural and environmental issues. Land use and management affect food production and economic growth and play crucial roles in the health and sustainability of ecosystems (Seaton et al., 2021). As a result, the balance between human needs and environmental conservation depends on the extent to which we understand the impacts of different land use practices on soil properties. From this perspective, one of the best indicators of soil health is its structure. It is a key factor in the functioning of soils, impacting its capacity to sustain plant and animal ecosystems while also exerting a significant influence on environmental quality, particularly on soil carbon sequestration and soil nutrient dynamics (Bronick and Lal, 2005; Udeigwe et al., 2015). The influence of various environmental factors on soil structure is generally assessed by analysing changes in soil aggregates, which are the basic structural units of the soil. In this way, aggregate stability, which quantifies the vulnerability of soil aggregates to different stresses (tillage, water erosion and wind erosion), has been used to analyse changes in soil structure.

The stability of soil aggregates influences their ability to carry out ecosystem functions, including food and fibre production, climate change mitigation, groundwater purification, and habitat for soil biodiversity (Okolo et al., 2020). Numerous studies have further demonstrated that soil aggregates protect organic matter (OM) from mineralisation, whereas OM is the main binding agent for many soil types. While reviews like the one by Six et al. (2004) discussed how important soil aggregates are for storing carbon in the soil, emerging trends suggests that many other ecological functions are now being linked to soil aggregates (Bimüller et al., 2016; Bach et al., 2018). In addition, there is a growing body of work exploring the role of soil aggregates in the contingency of environmental problems such as eutrophication (Soinne et al., 2014; Li et al., 2024) and heavy metal pollution in soils (Zhang et al., 2003; Wang et al., 2021).

Therefore, an in-depth examination of the ecological and environmental roles of soil aggregates is important. It is also instructive to explore how land use or land use change regulates these functions. However, the relevance of such a discussion is contingent upon a comprehensive and understanding of the up-to-date knowledge on the mechanisms underlying soil aggregate formation processes. The aim of this review is therefore to: (i) provide an up-to-date and comprehensive discussion of the pathways by which soil aggregates are formed, (ii) fully explore the roles of soil aggregates in the delivery of soil ecosystem functions (iii) critically examine the impact of land use and other environmental stressors on soil aggregates and associated environmental and ecosystem functions, and finally, (iv) identify areas for future research in the issues surrounding soil aggregate dynamics and their environmental and ecological roles.

2 Overview of soil aggregate formation mechanisms

Soil aggregates are generally understood to be discrete physical units formed by the association of organic and mineral particles bound together in such a way that their cohesion is stronger than that of neighbouring entities. The concept that soil structure depends on aggregates is one of the most topical debates in soil science, highlighting two contradictory schools of thought (Garland et al., 2024; Roosch, 2024). On one hand, a conceptual view of soil structure based on the organisation of aggregates highlights a structuring into discrete physical units (aggregates). This perception can be considered traditional, based on a hierarchical organisation of the soil structure (Tisdall and Oades, 1982). On the other hand, a recent trend in research shows that the functional importance of soil structure lies mainly in its pore network, rather than in the observable aggregates. They emphasise the continuity, tortuosity, connectivity, and size distribution of pores, which govern water flow, gas diffusion, root growth, and microbial habitats (Rabot et al., 2018; Johannes et al., 2019). This apparent discrepancy can be explained by the fact that in undisturbed soils, particularly in deeper horizons or certain natural ecosystems, clearly defined, "levitating" aggregates with distinct boundaries are not always visible (Garland et al., 2024). Destructive methods of separating soil aggregates (Dry and wet sieving) are also criticised for creating artefacts that do not reflect the structure *in situ* (Siebers et al., 2018). Moreover, some scientists argue that focusing solely on aggregates or their stability misses the overall picture of how the continuous pore system works (Koestel et al., 2021; Baveye et al., 2022). While the debate can sometimes seem polarised, the prevailing feeling among many soil scientists is that both points of view are essential and complementary. In fact, aggregates are not independent entities, their formation fundamentally creates the pore network. The spaces between the aggregates form the macropores and the spaces within the aggregates form the micropores (Garland et al., 2024). Thus, research should move towards integrative approaches that combine knowledge from both perspectives, using advanced imaging to link aggregate morphology to pore network properties, and understanding how different management practices influence both (e.g., Amelung et al., 2024).

The above debate is fundamental to understanding the influence of structures on the functioning and ecosystem dynamics of the soil. Several studies, based initially on the mechanistic model and/or recently on more complex numeric models, have highlighted the need for a comprehensive review of the environmental and ecosystem roles of soil aggregates.

In early research on soil aggregate formation and stability, OM was considered the critical binding agent for soil aggregate formation and stability. Several conceptual models, which have evolved over time and with new information, have been used to describe the formation of soil aggregates. One of the most empirical examples is that of Emerson (1959), who described soil aggregates as "crumbs". According to this conceptual model of aggregate organisation, the stability of soil crumbs is influenced by the binding of clay domains to quartz particles via OM, which is considered to as the only natural binding agent within soil aggregates. This binding prevents disintegration and dispersion, particularly when the soil is wet. Although the contribution of clays and OM to the consolidation of aggregates in clay-rich soils is highlighted in this model, it appears far too simplistic. The role of soil organisms and microorganisms in the formation of aggregates, even though it has been emphasised in previous studies (Martin et al., 1955), is not included in this model. Moreover, it makes no distinction between the types of soil aggregates because of an oversimplification of the actions and interactions between soil components.

The idea of aggregate varying with size and property was introduced by Edwards and Bremner (1967) with the microaggregate theory. According to this theory, soil with a high base status consists of the basic structural units of fine sand and fine silt. These units, called microaggregates (<250 μm), form through solid–phase interactions involving clays, polyvalent metals, and OM (Equation 1 shows the microaggregate organisation according to Thomaz et al., 2022).

$$\left[(C-P-OM)_x\right]_y \tag{1}$$

where C represents clay mineral particles, P represents polyvalent metals (Ca, Fe, and Al), and OM represents the organometallic complex. This model is the first to introduce the idea of a certain difference in the formation process between aggregates of different sizes. Additionally, the OM incorporated into these microaggregates is physically protected and inaccessible to microorganisms.

Tisdall and Oades (1982), with a key modification Oades (1984) proposed another mechanistic model for the formation and stabilisation of aggregates, emphasising the hierarchical organisation of aggregates and the distinct roles of the various organic binding agents at different scales. Aggregates are categorized into microaggregates (<250 μm) and macroaggregates (>250 μm). The organic binding agents are classified into three categories based on the age and degradation of OM: (i) transient binders (e.g., microbial polysaccharides), which are short-lived (a few weeks to a few months). They are effective in forming and stabilising macroaggregates. Their rapid turnover reflects a strong dependence of macroaggregate stability on continuous inputs of fresh OM and microbial activity (ii) temporary binders (e.g., roots, fungal hyphae); which have an intermediate longevity (months to years). They are involved in the physical enmeshment of particles and microaggregates to form macroaggregates; (iii) persistent binders (e.g., highly decomposed OM substances, organo-mineral complexes). They are long-lived (years to decades or centuries) and are mainly responsible for the stability of microaggregates and sub-microaggregates fractions. They are tightly adsorbed onto mineral surfaces, providing strong chemical and physical protection. However, soil aggregates are pictured as static components, though the authors acknowledge that tillage disturbs the macroaggregate fraction.

A dynamic view of soil aggregation has been introduced by Six et al. (2004), revealing that the turnover of soil aggregates is governed by soil fauna, microorganisms, roots, inorganic binders and environmental factors, mainly climatic. This dynamics is coupled to that of the soil organic carbon (SOC), with the microaggregates acting as long-term protection for the SOC, while macroaggregate turnover is fundamental to the protection of the microaggregates that are occluded within them. This perception has helped to paint a more complex picture of the formation of soil aggregates, highlighting the role of aggregates as crucial mediators in the global carbon cycle. By providing a theoretical basis for understanding the effects of land management on the sequestration of SOC within soil aggregates, it attributes an ecosystem function to them. However, the proposed vision focuses largely on the role played in the carbon cycle when many ecological functions remain unexplored.

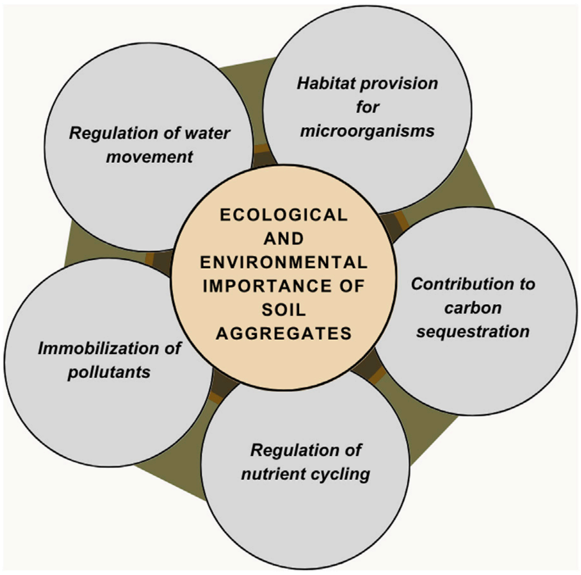


FIGURE 1
Ecological and environmental function of soil aggregates.

Soil aggregates are also considered through a formation model in which biological processes predominate. This mechanistic model, described as biogenic, emphasises the major role played by edaphic fauna, flora and soil microorganisms (Pereira et al., 2021; Guhra et al., 2022). Although all the processes surrounding this aggregation pathway have not been thoroughly investigated, Guhra et al. (2022) show that in the case of aggregates resulting from biologically excreted OM, intervention in aggregate formation occurs either as (i) a binding agent which promotes aggregation due to surface modifications and attraction, (ii) a separating agent which promotes the formation, mobility and transport of organo-mineral associations and inhibits their subsequent inclusion in aggregates, and (iii) a gluing agent which ensures aggregate stability. The description of these mechanisms highlights the major role played by aggregates in ecosystem functions such as SOC sequestration and the provision of habitat for soil microorganisms.

Some numerical models have also been considered to explain the formation of soil aggregates either for specific microaggregate fractions (Ritschel and Totsche, 2019), or to consider specific mechanisms (Meurer et al., 2020; Brangarí et al., 2021; Laub et al., 2024; Nascimento et al., 2024). However, they have so far failed to adopt an approach that integrates all the aggregate fractions or components of soil aggregation. Nevertheless, most of these models establish a relationship between soil aggregates and one or more ecosystem functions.

In summary, soil aggregate formation has been examined through many conceptual models. Current mechanistic and numerical models have succeeded in providing an overview of soil aggregate formation, but the development of a more holistic model is needed. Furthermore, an in-depth analysis of current knowledge on the contribution of aggregates to ecosystem functioning can highlight the role of soil aggregates as an indicator of soil health.

3 The roles of soil aggregates in ecosystem functions delivery

Soil aggregates are at the heart of many environmental issues and influence numerous ecological processes within the soil. They influence the retention and circulation of water and air in the soil (Yudina and Kuzyakov, 2023; Eze et al., 2025); they are home to diverse microorganisms that, along with soil colloids (clays, oxyhydroxides, OM), regulate the cycles of the main nutrients and help fix certain pollutants (Bach et al., 2018; Mhete et al., 2020). In addition, the stability of aggregates is essential for preventing erosion, as stable aggregates resist degradation by rain and wind, protecting the soil from nutrient loss and degradation (Zheng J. Y. et al., 2021). Understanding and preserving the stability of soil aggregates is therefore essential for maintaining soil productivity, mitigating climate change and supporting ecosystems that depend on healthy soil functions. The aforementioned functions of the soil significantly contribute towards achieving almost all the United Nations Sustainable Development Goals (Lal et al., 2021). In this section, we review the essential elements of soil aggregate interventions on ecological and environmental processes. The essential ecological and environmental roles of soil aggregates is presented in Figure 1.

3.1 Habitat for soil microorganisms

Soil aggregates provide a habitat for a diverse range of microorganisms. According to Six et al. (2004), Coleman and Elliot (1988), have demonstrated the organisation of microorganism communities within soil aggregates as a function of the hierarchisation of pores between aggregates: the larger macropores are home to microarthropods; the pores between macroaggregates are mainly occupied by nematodes; the pores between microaggregates within aggregates are occupied by small nematodes, fungi and protozoa; while the pores within aggregates are occupied by bacteria. Nevertheless, recent studies have drawn up a more complex picture of the distribution of microorganism communities within soil aggregates. It is becoming increasingly evident that many biological interactions are regulated by soil aggregates (Gupta and Germida, 2015). Some research has even demonstrated that, compared with bulk soil, aggregates contain a greater diversity of microorganisms, especially fungi and bacteria (Bach et al., 2018; Xu et al., 2021). Soil aggregates are not only physical structures, but also hot spots for microbial life, often displaying greater biodiversity than the surrounding soil and protect microorganisms from predation (Pathan et al., 2021). There are various reasons for this: the first is the heterogeneity of the microhabitats. As explained in the hierarchical model, soil aggregation results from a combination of fractions of different sizes that create a multitude of distinct microhabitats with varying levels of oxygen, water content, nutrient availability and protection against environmental stresses such as desiccation or predation (Liao et al., 2022). This spatial heterogeneity within and between aggregates allows a greater variety of microorganisms to coexist, each adapted to specific conditions. For example, anaerobic bacteria can thrive inside large aggregates, which are deprived of oxygen, while aerobic fungi dominate the more porous exterior (Upton et al.,

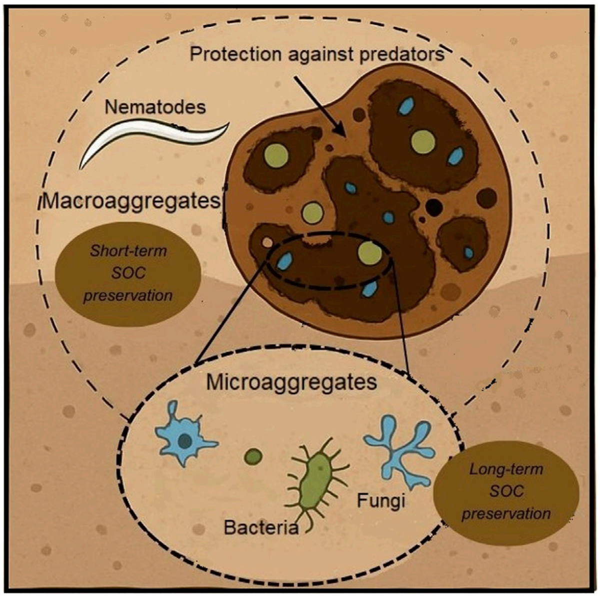


FIGURE 2
Soil aggregates, hotspots of microbial diversity.

2019). The second is the availability of resources. Aggregates often contain a higher concentration of OM, which is a primary food source for many soil microorganisms. This OM can be physically protected within the aggregate structure, making it a more stable and reliable resource than OM dispersed in the soil in bulk (Wiesmeier et al., 2012). The third is the protection resulting from the physical structure and connectivity. The complex network of pores within and between aggregates provides a variety of niches for colonisation. The different pore sizes and levels of connectivity favour the growth and movement of different microbial groups (Erktan et al., 2020). Finally, historical and colonisation factors also explain the high diversity within aggregates. Aggregates can be longer-lived than individual soil particles, providing a more stable environment for the development and succession of microbial communities over time (Sun et al., 2022). The process of aggregate formation can selectively trap and concentrate certain microbial groups as well as OM and minerals.

The distribution of microorganisms within soil aggregates is influenced by the presence of different aggregate fractions (Fox et al., 2018). However, the specific evolutionary trajectories of the major groups differ. While nematodes are more abundant and diverse in large soil aggregates (Briar et al., 2011; Jiang et al., 2018), bacteria and fungi, in contrast, appear to be more abundant and diversify in microaggregates (Biesgen et al., 2020; Zheng W. et al., 2021). Figure 2 shows an overview of the interaction between microorganisms within soil aggregates. This difference in the location of microorganism communities within soil aggregates can be attributed to the predation relationship between these groups. The high level of predation by protists and nematodes in macroaggregates limits the diversity of bacteria and fungi, which are found in microaggregates where they are less exposed to predators (Jiang et al., 2023). It has been proven that these trophic relationships are important determinants of agricultural productivity (Li F. et al., 2018; Wang R. et al., 2017). They contribute to the carbon (Martin and Sprunger, 2021; Modak et al., 2019) and nutrient (Liao et al., 2018; Li F. et al., 2019; Abd Elnabi et al., 2023) cycles. Nevertheless, this delicate equilibrium can be disrupted by inappropriate agricultural practices (Wang Y. et al., 2017; Wu et al., 2021).

3.2 Carbon sequestration

The stability of soil aggregates plays a crucial role in the physical protection of OM from microbial degradation, thereby facilitating the accumulation of SOC within aggregates and ultimately enhancing carbon sequestration (Noormets et al., 2014). The relationship between aggregate stability and soil carbon sequestration is well documented, with aggregate stability playing a critical role in the ability of soil to sequester carbon (Figure 3). Numerous studies have established the connection between these two processes, demonstrating that soil aggregates are fundamental for carbon sequestration through various mechanisms (Blanco-Canqui and Lal, 2004; Le Bissonnais and Le Bissonnais, 2016).

The hierarchical conception of soil aggregation is fundamentally based on the close link between the SOC cycle and soil aggregates. This link is crucial for both soil aggregate dynamics and SOC sequestration as thoroughly explained by Six et al. (2004). According this study, long-term SOC sequestration in soil aggregates is generally governed by the degree of physical protection of particulate organic matter (POM) in microaggregates, i.e., the entrapment of organic particles within microaggregates. Six et al. (2004) simply describe the long-term sequestration of SOM in the form of POM through several distinct stages. Initially, the fresh OM is transformed into coarse intra-aggregate POM (coarse iPOM) within macroaggregates. The coarse iPOM is then decomposed and fragmented into fine iPOM (53–250 µm). Finally, the fine iPOM and its associated mucilages become encrusted with minerals to form the stabilised organic core of a microaggregate that develops within macroaggregates. This process serves to physically protect OM from both physical and chemical degradation by microbes. However, this process is highly dependent on the turnover of the macroaggregates within which the microaggregates are protected. The breakdown of macroaggregates leads to an increase in OM mineralisation and the loss of SOC. Macroaggregates therefore store SOC in transient form, while microaggregates store it in a more stable form. Furthermore, macroaggregate turnover is controlled by a range of factors including soil fauna, inorganic binders and environmental variables.

The chemical stabilisation of SOC by interaction with the surface of mineral particles (clays and iron and aluminium oxides) into mineral-associated organic carbon (MAOC) is also recognised as a serious pathway for the long-term stabilisation of SOC within soil aggregates (Manzoni and Cotrufo, 2024; Iroshaka Gregory Marcelus Cooray et al., 2025). In a brilliant review discussing the mechanisms of SOC stabilisation by minerals mediation, Xu and Tsang (2024) showed that sorption of SOC by minerals is the dominant pathway for the formation of highly stabilised MAOCs. This sorption results either from complexation, ligand exchange, electrostatic interaction, and/or the bridging of cations.

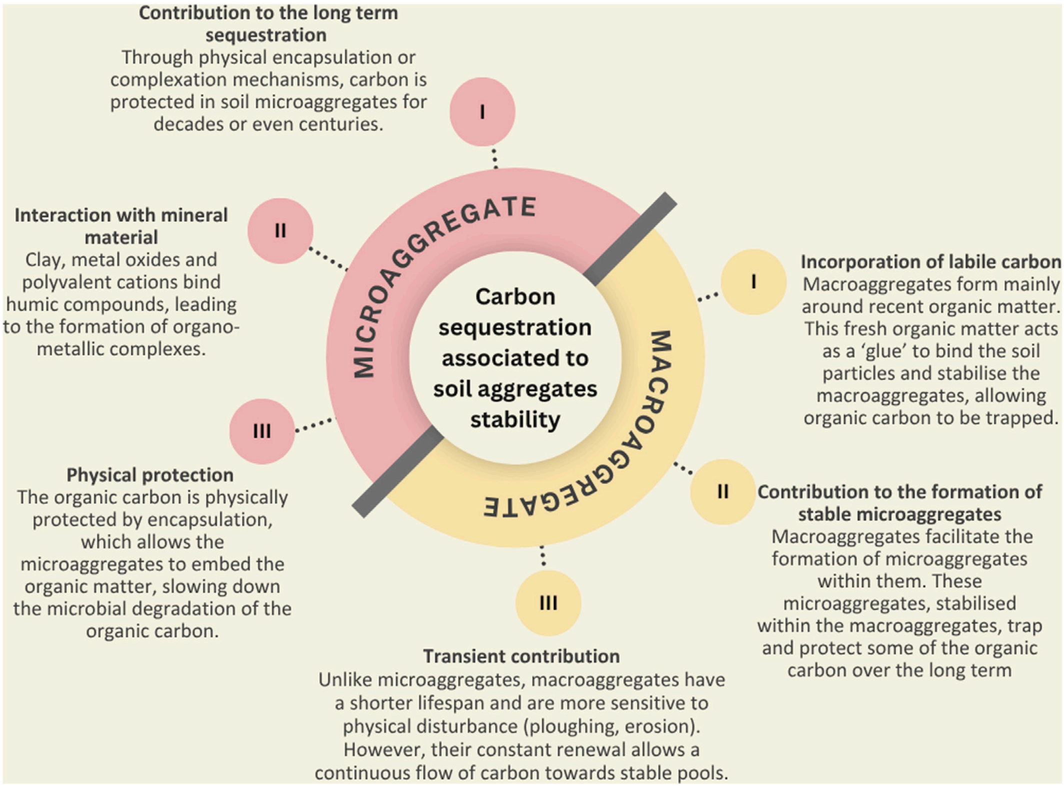


FIGURE 3
Relationship between aggregate stability and carbon sequestration.

Several studies have also demonstrated the significant contribution of the biogenic pathway to the long-term stabilisation of SOC in soil aggregates (Melo et al., 2019; Zhang et al., 2023; de Oliveira Sales et al., 2025). Two main types have been highlighted: SOC excreted by soil fauna; and microbial necromass. Earthworms and termites ingest fresh OM, which is combined with mineral particles in their guts. The microorganisms coexisting in their digestive tracts play a crucial role in promoting the formation of biogenic aggregates, which are then excreted (Eze et al., 2020; Guhra et al., 2022). On the other hand, microbial necromass refers to the non-living biomass of microbes. It results from the death of microbes due to predation, stress or natural renewal. Microbial necromass, particularly that of bacteria, contains amino sugars (e.g., muramic acid, glucosamine) and peptides that have a strong binding capacity with clay minerals and metal oxides (Salas et al., 2024), leading to the formation of biogenic aggregates. As shown by Zhang et al. (2023), the carbon contribution of microbial necromass can represent up to 44% of the total SOC sequestered in soil aggregates. Nevertheless, the sequestration mechanism and sustainability of this pathway are not yet well understood.

In fact, as some studies have demonstrated, the stabilisation of SOCs within aggregates is generally the result of a coaction between these different pathways (Zhang et al., 2024; Zhao et al., 2025a). This has even led to the development of numeric models that could guide the planning of sustainable soil health management (Laub et al., 2024; Manzoni and Cotrufo, 2024). While the ability of aggregates to stabilise has hitherto been linked to aggregation status, which places the factors influencing aggregation in the spotlight (Six et al., 2004), Even and Francesca Cotrufo, (2024), have recently shown that soil's ability to aggregate is the key factor in determining the ability of the SOC to stabilise in soil aggregates. This discrepancy therefore opens a decisive avenue for future research into improving SOC sequestration within aggregates.

3.3 Nutrient regulation and pollutant fixation

Through the complexing power of its colloidal fraction and the action of microorganisms, soil aggregates play a fundamental role in temporary immobilization and the subsequent availability of nutrients (Udeigwe et al., 2011; Cui et al., 2020). Soil aggregates can also intervene in the fixation of certain soil pollutants (Li and Gong, 2021). This section discusses the influence of aggregates on the phosphorus, nitrogen and potassium cycles, as well as their role in the fixation of heavy metals.

3.3.1 Influence of aggregate stability on the phosphorus cycle

Soil phosphorus is a major nutrient for plant productivity. However, excess phosphorus in the soil is associated with eutrophication. This is a critical environmental problem linked to modern agriculture, which is based on the intensive use of inorganic fertilizers (Mng'ong'o et al., 2022). As a result, considerable efforts are being made to reduce the loss of phosphorus through wind and water erosion. A substantial body of research has demonstrated the role of soil aggregates in mitigating phosphorus loss in soils (Garland et al., 2018; Li F. et al., 2020).

The amount of phosphorus stored and its capacity to be stored sustainably depends on the size of the aggregates (Zhang et al., 2025). It has been shown that microaggregates have a greater capacity to store phosphorus in the long term than macroaggregates (Li et al., 2016; Cui et al., 2024). This high fixation capacity of microaggregates is explained by their higher adsorption-desorption potential than that of macroaggregates (Liu C. et al., 2024). As explained in Section 3.2, SOC sequestration can, in some cases, result from interaction with minerals. In fact, these are organo-mineral complexes (clay-SOM-metal oxide) which have a high sorption capacity for cations and metal ions (Liu S. et al., 2024).

Nevertheless, the ability of soil aggregates to protect phosphorus from loss through erosion depends on the degree of soil stability. In other words, the ability of macroaggregates to preserve microaggregates. Microaggregates occluded within macroaggregates secure fixed phosphorus, which is not the case for free microaggregates, easily detached by erosion (Zhao et al., 2023). Moreover, Aggregates safeguard OM, which constitutes a significant portion of the soil's organic phosphorus (Garland et al., 2018). Phosphorus is less readily available in the short term, but it is slowly released through the mineralisation of OM by microorganisms (Xie et al., 2024; Cui et al., 2025). As previously discussed, soil aggregates create a favourable habitat for soil microorganisms that contribute to the ecological cycle of the soil. Therefore, aggregates play a significant role in regulating phosphorus, facilitating its availability to plants, typically through macroaggregates that contain the largest proportion of labile phosphorus, whereas microaggregates more durably fix phosphorus.

3.3.2 Influence of aggregate stability on the nitrogen cycle

Nitrogen is one of the most important nutrients for plant growth and productivity, but excess nitrogen in the soil, mainly due to the misuse of inorganic nitrogen fertilizers, is linked to critical environmental and ecological issues such as eutrophication (Kelly et al., 2021), soil acidification and greenhouse gas emissions (Shoghi Kalkhoran et al., 2019). Carbon and nitrogen dynamics in the soil are strongly connected, particularly through the decomposition processes of OM, which are involved in the nitrification and denitrification processes that contribute to gas exchange with the atmosphere and affect greenhouse gas emissions (Kong et al., 2007; Okolo et al., 2023). Soil aggregates have been shown to play a pivotal role in terrestrial geochemical nitrogen cycling. A substantial body of research has demonstrated a robust correlation between aggregate stability and nitrogen storage in the soil (Mustafa et al., 2020; Acharya et al., 2024; Yuan et al., 2024). Soil aggregates exert a significant effect on nitrogen dynamics within the soil, both directly and indirectly. It has been demonstrated that soil aggregate stability impacts the immobilization of nitrogen, thereby reducing losses through leaching or volatilization (Chen et al., 2024a; Udeigwe et al., 2015). Additionally, it regulates the mineralisation and gradual release of inorganic nitrogen (Liao et al., 2021). Furthermore, it provides a favourable habitat for the microorganisms involved in the nitrogen cycle, thereby reducing nitrogen losses in gaseous or dissolved form and improving nitrogen efficiency in agricultural and natural ecosystems (Yuan et al., 2024). Numerous studies have also examined the contribution of aggregate size to soil nitrogen dynamics. Thereby confirming that macroaggregates are involved in the short-term conservation of nitrogen which is gradually released for plants, while microaggregates are involved in the long-term protection of nitrogen (Lopez-Bellido et al., 2017; Comin et al., 2018). Nevertheless, as explained for SOC and phosphorus, macroaggregates plays a crucial role in nitrogen long-term protection within microaggregates, by providing them a protection (Hao et al., 2024).

Furthermore, nitrogen sequestration in soil aggregates is strongly influenced by certain factors, such as cropping systems, plant communities and species or the use of chemical fertilizers or organic amendments (Udom and Ogunwole, 2015; Sekaran et al., 2021). Although a great deal of research is progressively analysing the influences of each of these factors on aggregate-associated nitrogen, it is important to explore the development of such lines of research in view of the ecosystemic and environmental importance of aggregate-associated nitrogen.

We have focused the discussion on phosphorus and nitrogen given the abundance of recent scientific work addressing the role of soil aggregates in the cycling of these two macronutrients. There are also some studies that present a major role for soil aggregates in the adsorption-desorption of potassium in soils (Yuan et al., 2023; Xu et al., 2025). Furthermore, while calcium is often mentioned as an aggregating agent (Vargas et al., 2019), it would also be interesting to analyse the influence of soil aggregates on its cycle.

3.3.3 The role of soil aggregates in heavy metal fixation

Heavy metals (metallic elements with a relatively high density, generally greater than 5 g/cm^3, including lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), copper (Cu), zinc (Zn), nickel (Ni) and chromium (Cr)) pollution represents one of the most significant contemporary environmental and public health concerns (Eze et al., 2010; 2019; Abd Elnabi et al., 2023; Kouadio et al., 2024). The release of these chemical elements, which can be naturally occurring or anthropogenically introduced into the environment, has the potential to lead to several health risks, including cancer, as well as detrimental impacts on plant and animal ecosystems. Nevertheless, the implementation of techniques for rehabilitating or restoring degraded soils indicates that aggregate stability can be regarded as an effective method for the fixation of these pollutants in the soil. Wen et al. (2022) demonstrated the role of soil microaggregates in the stabilisation of chromium and cadmium, whereas Wang et al. (2021) reported that the increased stability of aggregates resulting from organic soil amendments (biochar) was linked to reduced leaching of heavy metals, leading to a decrease in the bioavailable fraction of cadmium and the fixation of metals in less labile forms (e.g., the residual fraction). In this way, the risks of transfer to the plant and the environment are reduced. Mitchell et al. (2020) also reported that more stable aggregates help reduce the mobility of copper, chromium and arsenic in the soil. The binding mechanisms are mainly linked to organic and inorganic agents such as iron oxide, OM and clay particles (Li T. et al., 2020; Spadini et al., 2018). The distribution of heavy metals within aggregates varies according to aggregate size. Huang et al. (2014) reported that finer aggregate fractions have a greater capacity and faster adsorption rate for Cu and Zn because of their greater specific surface area, OM content and high cation exchange capacity. Farshadirad et al. (2019) reported that the copper fixed by macroaggregates is more readily available to plants than the copper fixed by finer particles (0.25–0.2 mm). The adsorption-desorption of heavy metals within aggregates is also controlled by factors such as pH. A decrease in soil pH is associated with desorption, whereas an increase in pH has the opposite effect (Huang et al., 2014). The type of soil amendment and land use system also influence the potential for heavy metals to be adsorbed into aggregates. Certain organic fertilizers, such as biochar, improve the fixation of heavy metals in the aggregates, whereas other fertilizers increase the acidity of the soil, resulting in the leaching of heavy metals (Deng et al., 2018; Wang et al., 2021; Ma et al., 2022).

3.4 Soil water flow, retention and erosion control

The various movements of water on the soil surface or through the soil (runoff, infiltration, retention and availability to plants) are linked to its structure, the basic unit of which is the aggregate. Consequently, the ability of a soil to resist the disruptive mechanical action of a rainfall splash or the disruption caused by runoff is also a function of its cohesive capacity (Abu-Hamdeh et al., 2006), which is highly dependent on the stability of the aggregates. In fact, water flow in the soil is determined by its degree of aggregation. Carminati et al. (2007) reported that water flow in soil is strongly controlled by the contact surface between aggregates. When these contacts are too tight, they reduce water circulation. Moreover, soil aggregates, and more specifically, the size of the aggregates, have a major influence on the water holding capacity (WHC) of the soil. The water retention capacity varies according to the aggregate size and soil type (Gu et al., 2025). Compared with larger aggregates, small aggregates (<0.25 mm) retain water more effectively at higher pressures (Guber et al., 2004; Lipiec et al., 2007). In addition, soil aggregates help combat compaction by improving structural stability, porosity, and water circulation and by supporting soil biology (Yang T. et al., 2024). Their presence promotes a more resistant and resilient soil capable of withstand pressure while maintaining conditions conducive to plant growth and ecosystem health (Carminati et al., 2008).

One of the prominent form of soil degradation today is erosion, either by water run-off in rainy environments or in irrigated agriculture or by wind in arid environments. Because of its contribution to soil cohesion, improving soil aggregation is one of the most effective ways of combating erosion. Numerous studies have clearly demonstrated that the type of land use, whether favourable or unfavourable to the stability of soil aggregates, influences the ability to resist soil erosion. For example, Zhu et al. (2022) reported that changes in land use, from tropical forests to rubber plantations, increase the vulnerability of soils to erosion by modifying the stability and size distribution of aggregates. Integrating OM into intercropping systems improves soil stability, reduces the risk of erosion and supports sustainable land use in southwestern China.

To summarise, soil aggregates play a central role in many environmental and ecosystem functions of the soil, including (i) providing a habitat for soil flora and fauna, regulating predation interactions; (ii) they play an essential role in carbon sequestration, long-term storage within microaggregates occluded in macroaggregates; (iii) they influence nutrient fixation, reducing environmental issues such as eutrophication; (iv) they contribute to the reduction of water pollution by fixing heavy metals; (v) in addition, soil aggregates also contribute to the circulation and retention of water in the soil and to erosion control. The role of aggregates as influenced by land use systems is critically examined in the following section.

4 Impact of land use and farm management on environmental and ecosystem functions of soil aggregates

Land use and land use changes can significantly impact soil aggregate stability and distribution. This disturbance can lead to deterioration in the ecosystem and environmental functions of the aggregates (Gelaw et al., 2015; Okolo et al., 2020; Hu et al., 2023). In turn, these changes can affect the overall health and productivity of the soil. Investigating the relationships among land use, aggregate stability, and ecological and environmental functions delivery is vital for comprehending the distinct roles that various aggregate types play in maintaining soil health.

4.1 Impacts of land use change and environmental stressors

4.1.1 Fallow land

Fallow land is arable land that is left uncultivated for a period, typically one or more growing seasons, to allow for the recovery of its fertility (Deore and Pethkar, 2022). In practice, fallow is a generic term that encompasses a variety of land-use techniques aimed at restoring soil health. Compared with cultivated soils, fallow soils generally present a much-improved structure (Abán et al., 2025). When agricultural land is left fallow, aggregate stability is enhanced due to reduced physical disruption and the accumulation of OM, especially in the upper layers of the soil (Figure 4). Fallow practices promote the formation of macroaggregates, which are crucial for improving soil structure and stability. Burdukovskii et al. (2020) reported that soils with a relatively high content of macroaggregates tend to be relatively stable and resilient. Similarly, Dowuona et al. (2011) demonstrated that, compared with cropping systems, fallow systems significantly promote macroaggregate formation, leading to better aggregate stability and overall soil health. For example, 51.3% of the aggregates in fallow land were larger than 0.25 mm, whereas in cropping systems, more than 75.9% of the particles were smaller than 0.25 mm (Kou et al., 2012). Over extended fallow periods, soils exhibit morphological changes, and this reflects the ability of the soil to accumulate and retain OM and build a more resilient surface layer over extended periods without disturbance (Burdukovskii et al., 2020).

Despite the benefits of fallow systems in promoting macroaggregate formation, fallow periods with manure application can be more effective at increasing SOC and maintaining high crop productivity by providing additional OM

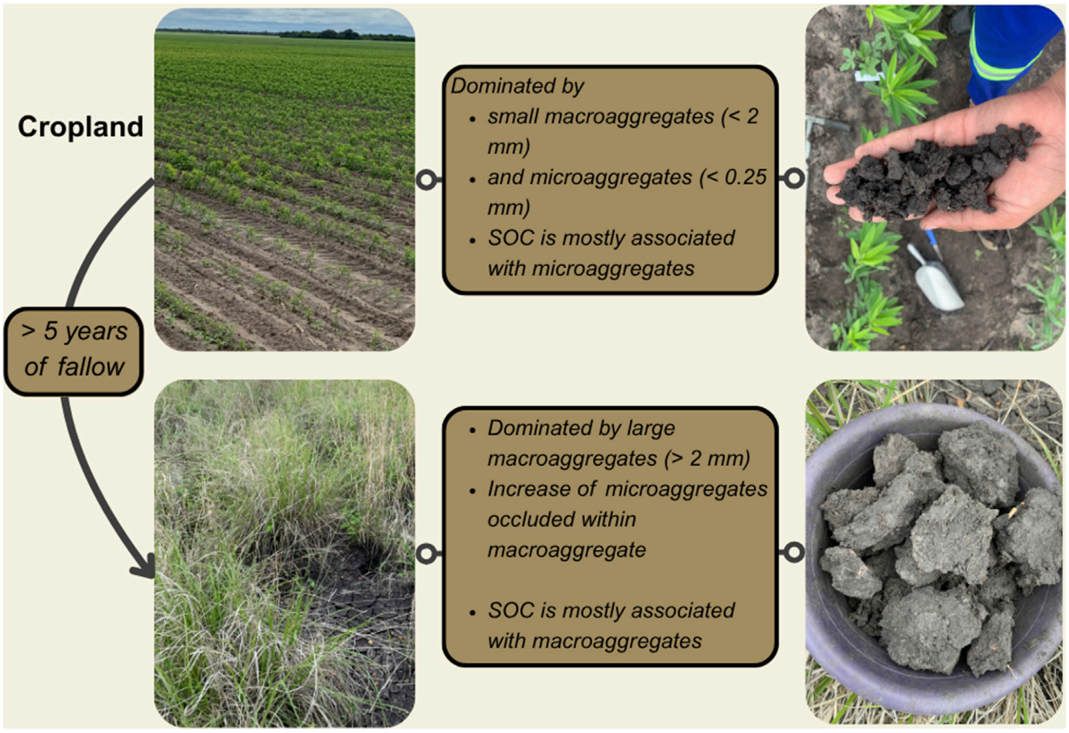


FIGURE 4
Effects of the conversion of cropland to fallow on aggregate size distributions and SOM.

(Manna et al., 2007). However, alternating fallow periods with crops such as corn or soybean have been shown to be more effective at forming water-stable aggregates (Zhou et al., 2020). Fallow-corn and soybean–corn rotations significantly improved soil aggregates stability, promoting more stable soil aggregate structures. The benefits were attributed to reduced soil aeration from no-tillage practices and increased SOC storage due to legume and grass crop rotations, which enhance the soil structure and stability (Yang et al., 2022).

During fallow periods, minimal soil disturbance allows plant biomass to accumulate and integrate into the soil, fostering the formation of stable macroaggregates. This process not only improves the soil structure but also enhances long-term SOC storage. Additionally, the type of plants grown during the fallow period plays a crucial role in biomass production and carbon sequestration, emphasising the need to select species that maximize both biomass input and soil stability during the fallow period.

Moreover, the positive influence of fallow on the stabilisation of SOC in soil aggregates also contributes to promoting the biodiversity associated with aggregates (Agnihotri et al., 2022; Ducci et al., 2024; Li G. et al., 2018), improving nutrient fixation and pollutant retention (Liu et al., 2023), as well as the circulation and retention of water in the soil (García-González et al., 2018; Williams et al., 2022). Nevertheless, more detailed study is needed to quantify the respective benefits of the different fallow systems for each of the ecosystem and environmental functions of soil aggregates.

4.1.2 Grassland

Grassland is defined as an area where the dominant vegetation consists of grasses and other herbaceous plants, with limited cover of trees or shrubs (generally less than 10%). These areas are characterised by open, continuous landscapes, often situated between temperate forests and deserts. Grassland types include meadows, prairies, rangelands, savannahs, steppes or tundra, often referred to as natural grasslands (Sanderson et al., 2009). They play a critical role in maintaining soil aggregate stability and the related soil ecosystem and environmental functions (Cui and Holden, 2015; Garcia-Franco et al., 2021; Zhang X. et al., 2022). The extensive root systems and surface plant biomass in grasslands promote the formation of stable macroaggregates (Kemner et al., 2021). Additionally, the accumulation of surface litter in grasslands enhances OM and microbial activity, which results in the aggregation of smaller aggregates into more stable, larger structures (>0.25 mm) (Zhao et al., 2025b).

Several studies have shown a significant increase in the quantity of SOC associated with macroaggregates in the topsoil of natural grassland, and a decrease in microaggregates (Shrestha et al., 2007; Dorji et al., 2020; Dong et al., 2022). Saha et al. (2011) reported that, compared with other land uses, grasslands presented the highest aggregate stability in the topsoil (0–15 cm), whereas forest soils had the most stable aggregates in the subsurface layer (15–30 cm). Thus, natural grasslands are characterised by increase in soil structuration, associated to increase in SOC sequestration in topsoil horizon. This can be explained by root activity as roots of plants in grassland are mostly superficial (Yost et al., 2016). Grasslands typically maintain high SOC stocks due to the substantial input of organic residues into the soil. Gelaw et al. (2015) reported that the SOC stock in topsoil was 88% greater in grasslands (30.4 mg ha^{-1}) than in other land uses, although SOC declined notably in the subsoil. Grasslands also presented greater macroaggregate-associated organic carbon, underscoring the critical role that macroaggregates play in carbon sequestration within these ecosystems.

However, Li et al. (2023b) noted a significant decreased of aggregates stability in the order of forests > grasslands > croplands in topsoil. These inconsistencies in the findings on aggregate stability between forests and grasslands could be attributed to the amount of plant residue returned to the soil. This plant residue acts as a vital framework in macroaggregate formation. With minimal disturbance, natural grasslands contribute to more SOM, where slow decomposition promotes greater aggregate stability. Surprisingly, paddy fields, despite heavy human intervention, have been found to exhibit greater aggregate stability than grasslands do, largely due to their unique water management systems, which increase SOC levels and, in turn, enhance aggregates stability (Du et al., 2013).

The stability and abundance of larger soil aggregates in grasslands are essential to their ability to store and retain SOC, contributing to their overall carbon sequestration potential. Conversely, the conversion of grassland to cropland, often driven by the increasing demand for food, can significantly disrupt soil properties. As reported by (Zhang Y. et al., 2022), this conversion led to a greater proportion of microaggregates but a marked decline in the SOC associated with these microaggregates, resulting in an overall loss of SOC in the soil. SOC-rich microaggregates occluded within macroaggregates are crucial for carbon sequestration, as they protect OM from rapid decomposition, thereby increasing carbon stabilisation and sequestration within the soil (Six et al., 2002). Research on the ecological restoration of cropland to grassland has demonstrated significant improvements in soil aggregates stability, SOC and the microbial community associated with the aggregates after restoration (Xue et al., 2021; Yang et al., 2025). Vegetation recovery in restored grasslands increases SOM, which in turn fosters the development of soil aggregates and enhances soil microbial community (Prangel et al., 2024). Grassland restoration also promotes the fixation of nitrogen and phosphorus in soil aggregates (Du et al., 2025; Li F. et al., 2025). Furthermore, improvement in soil pore networks has also been associated with the restoration of grasslands previously subject to farming, leading to an enhancement in water infiltration and WHC (Ajayi et al., 2021; Ren et al., 2023). Thus, grasslands are an effective natural solution for improving several ecosystem and environmental functions linked to soil aggregates. However, an in-depth analysis should also pay particular attention to the influence of grasslands on the fixation of heavy metals or other pollutants in soil aggregates.

4.1.3 Forests

According to the FAO, a forest is defined as land of more than 0.5 ha with more than 10% tree cover and trees more than 5 m tall (or with the potential to reach this height). It excludes land primarily used for agriculture or urban purposes. Forests play important roles in carbon sequestration and aggregate stability because they can store large amounts of SOC in both above- and below-ground biomass. Forests with dense vegetation cover support the formation of SOM, which helps to store carbon over time (Mayer et al., 2020). The dense network of roots in forests also improves soil structure and aggregate stability by holding soil particles together, minimizing erosion, and increasing water infiltration (Sedaghatkish et al., 2023). Liu S. et al. (2024) reported the highest proportions of macroaggregates and aggregates stability under forestland, regardless of soil depth compared to other land use. Thus, forest is associated to improve in aggregates stability and soil structuration in the topsoil and the subsoil as supported by other studies (Bogunovic et al., 2020; Peng et al., 2023). The observed improvement in soil structure in forests is linked to the improvement in SOC, via the SOM fraction associated with aggregates. As a result, the forest not only improves the aggregates' stability, but also carbon sequestration within the topsoil and subsoil (Zajícová and Chuman, 2019; Lyu et al., 2021). The improvement in subsoil aggregates is linked to deeper root activity in forests than in other types of land use, which also boosts the activity of microorganisms and promotes SOC sequestration within aggregates (Liu et al., 2019; Liu Y. et al., 2024; Witzgall et al., 2024). Moreover, aggregates stability and aggregates-associated SOC in forestland vary with trees species (Bai et al., 2024). This is due to the variation in the specific characteristics of trees (Demenois et al., 2018). However, forests with a wide diversity of tree species allow a greater improvement in soil aggregation and SOC sequestration (Erktan et al., 2016; Cai et al., 2023).

According to aggregate hierarchy theory, macroaggregates are crucial to soil structuring and indirectly aid in stabilising SOC since they provide a favourable internal framework for microaggregate development. Soil macroaggregates play a crucial role in maintaining soil fertility and are highly sensitive to land use and management. Converting forests to croplands often disrupts the soil structure, leading to the breakdown of macroaggregates (Liu X. et al., 2025; Wei et al., 2013). This process exposes SOCs that were previously protected within aggregates, increasing their susceptibility to microbial degradation. As a result, SOC is mineralised at a faster rate. The destruction of macroaggregates also increases the proportion of microaggregates, silt, and clay-sized particles in the soil, further altering its physical and chemical properties. The conversion of natural vegetation (forests, grasslands, and shrublands) to cropland is generally linked to the breakdown of macroaggregates by tillage and a consequent reduction in the SOC associated with these soil aggregates (Figure 5). This conversion is also associated with an increase in environmental issues such as eutrophication and heavy metal pollution (Deng et al., 2018; Bi et al., 2020). Moreover, it results in a reduction in soil biota (Li X. et al., 2019), WHC and water infiltration (Owuor et al., 2018).

Nevertheless, agroforestry has been shown to have a positive effect on the stability of soil aggregates and on the ecological and environmental functions associated with them. Barman et al. (2025) showed that long-term agroforestry promoted soil aggregation and SOC stabilisation in microaggregates in the Indian Himalayas. In general, compared with other farmlands, agroforestry lands are associated with an increase in soil fauna activity (de Oliveira Sales et al., 2025; Reis et al., 2025). Furthermore, agroforestry is related to nitrogen and phosphorous fixation in microaggregates occluded within macroaggregates (Monroe et al., 2022; de Oliveira et al., 2024; Lin et al., 2024). In addition, agroforestry also improves pore connectivity and water infiltration (Ngaba et al., 2024).

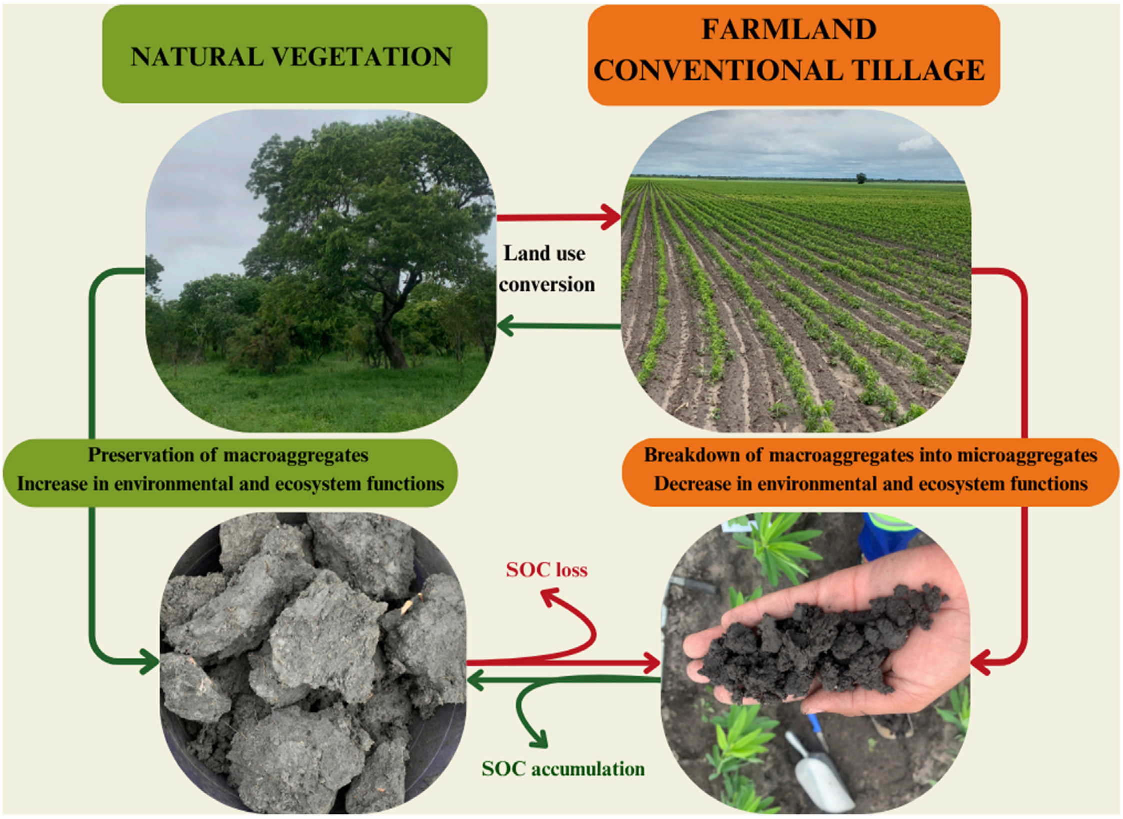


FIGURE 5
Effects of the conversion of natural vegetation to cropland on aggregate size distribution and the associated environmental and ecosystem functions.

Thus, the forest provides a major improvement in soil aggregation and the associated environmental and ecosystem functions in the topsoil and subsoil. While farming generally leads to soil aggregate deterioration, agroforestry systems help to reduce the damage caused and, in some cases, can even improve soil structure.

4.1.4 Wetland

Wetlands are essential transitional ecosystems characterised by soil saturation with water, either permanently or seasonally, during a significant part of the growing season, leading to the development of hydric soils and hydrophilic vegetation (Cowardin et al., 1979; Mitsch and Gosselink, 2015). The water is shallow enough to allow the rooting and growth of adapted vegetation, ranging from emergent macrophytes to woody species (Keddy, 2023). These diverse habitats encompass a wide range of types, including marshes, swamps, peatlands, fens and other areas defined by specific hydrological regimes and dominant vegetation forms, often delineated by established classification systems (Davidson, 2018). The aggregation dynamics of soils in wetlands are extremely sensitive to soil moisture conditions, which fluctuate considerably depending on seasonal hydrological changes. These fluctuations lead to critical wetting-drying cycles that profoundly influence the aggregate stability and the associated SOC (Kottkamp et al., 2022; Hou et al., 2024), nutrient bioavailability, and the activity of soil fauna and microbial communities (Tang et al., 2024). Nevertheless, the conversion of natural wetlands to farmland can lead to a deterioration in soil aggregate stability and SOC occluded in aggregates, as well as a decline in microbial communities (Liu Z. et al., 2024; Yavitt et al., 2021). Furthermore, environmental factors such as the freeze-thaw cycle have been shown to influence the mobility of phosphorus in wetland soil aggregates, highlighting the need to integrate these variables when considering changes in the environmental and ecosystem functions of soil aggregates (Cui et al., 2019; Li et al., 2022).

In summary, land use and land use changes have a profound influence on soil aggregate stability and associated ecosystem and environmental functions. However, further research is needed to provide a more comprehensive and quantitative analysis of the consequences of certain land uses or land use changes. For example, more emphasis should be placed on the conversion of natural land to urban land or the reverse. While it has been shown that farmland has a negative impact on soil aggregation and the associated environmental and ecosystem functions, this depends deeply on management techniques, particularly the fertilization and the tillage intensity.

4.2 Soil fertilization

Numerous studies have shown that appropriate fertilization improves the stability of soil aggregates, and the fixation of SOC and total nitrogen associated with the aggregates (Li Y. et al., 2020;

Yang X. et al., 2024). Moreover, soil fertilization influences the biological community and activity within soil aggregates (Li F. et al., 2019). However, inappropriate or excessive inputs are generally associated with environmental and ecological disturbances in the soil (Krasilnikov et al., 2022; Nuruzzaman et al., 2025). Besides, the influence of these fertilizers on soil aggregation and associated ecosystem and environmental functions varies considerably depending on the type of fertilizer (organic or inorganic) (Lin et al., 2025).

4.2.1 Organic amendments

SOM is an important indicator of soil quality since it improves a variety of soil quality indices. Several studies have demonstrated that sustainable management approaches can successfully increase SOC, which increases soil fertility and aggregate stability, resulting in increased agricultural production (Gautam et al., 2022; Xiao et al., 2022; Zhao and Meng, 2022). Moreover, a brilliant review of Sarker et al. (2022) has deeply analysed organic amendments effects on soil aggregation. They show that organic amendments improve soil aggregation by (i) increasing SOC content; (ii) promoting soil biotic activity; and (iii) increasing soil hydrophobicity. However, although the effects remain positive in general, they vary according to the type of organic amendment and some environmental factors. Given the wide variety of organic amendments, this article will simply discuss them in general terms. For clarification, in depth reviews on the subject are available (Tully and McAskill, 2020; Sarker et al., 2022; Ma et al., 2024).

Organic amendments treatments have been reported to effectively increased aggregates stability and aggregates-associated SOC (Mikha and Rice, 2004; Wortmann and Shapiro, 2008). In fact, the effectiveness of organic amendments in promoting the aggregation and sequestration of SOC in soil aggregates is attributed to the high quantities of carbonaceous chemicals, microbial biomass carbon and polysaccharides it contains, all of which increase microbial activity (Mikha et al., 2015). Furthermore, Mi et al. (2018) demonstrated that many organic amendments combined or applied alone (the combined application of farmyard manure, green manure and biofertilizers, or the application of composted or organic manure) all caused an increase in the fraction of macroaggregates, and the amount of SOC associated with macroaggregates in the topsoil. The carbon distribution within aggregates tends to increase with increasing aggregate size. Thus, organic amendments have in general a positive effect on soil aggregation and aggregates-associated SOC (Yilmaz and Sönmez, 2017; Feng et al., 2025). Moreover, increased organic amendments application improved soil quality by increasing SOC, total nitrogen, SOM, and fine and coarse POM (Singh et al., 2014). This increase in soil aggregates stability is also associated with improvement in the microorganism community and activity within soil aggregates (Chen et al., 2024b; Han et al., 2025; Tian et al., 2025), increase in nutrient and heavy metal fixation in soil aggregates (Milić et al., 2024; Li Q. et al., 2025), and enhancement of soil infiltration and pore connectivity (Tanha et al., 2024; Ju et al., 2025).

However, the influence of organic fertilizers on soil aggregates and associated environmental and ecosystem functions depends on several factors. Ma et al. (2024) reported that the dynamics of aggregates and associated carbon vary according to climate (mean annual rainfall and temperature), soil texture, initial SOC and nitrogen content, soil and fertilizer pH, and the C/N ratio of the fertilizer, which appears to be the most important factor.

4.2.2 Chemical fertilizers

The use of chemical fertilizers has improved agricultural productivity and contributed to the development of agricultural industrialisation, but their excessive and inappropriate use has raised major environmental concern (Zhang et al., 2018). The influence of chemical fertilizers on soil aggregation is the subject of contradictory debate. Some studies have shown that, despite a lesser improvement than that observed with organic amendments, chemical fertilizers also promote the stability of soil aggregates (Wang et al., 2025). Conversely, other research studies have shown that inorganic fertilizers significantly reduce the stability of soil aggregates (Yu et al., 2025). In fact, the influence of chemical fertilizers on soil aggregation is highly dependent on the rational application of fertilizers according to the plant's need and the fixation capacity of the soil. As shown by Howe et al. (2024), the rational application of chemical fertilizers has a positive influence on soil health, including aggregate stability. Moreover, environmental factors, especially climate, plant type and other soil properties should be also considered (Yang X. et al., 2024). Thus, chemical fertilizers influence on soil aggregate stability and aggregates-associated environmental and ecosystem functions. Numerous studies have analysed the influence of combinations of major elements, including nitrogen (N), phosphorus (P) and potassium (K), on the dynamics of aggregation and the accumulation of carbon within aggregates (Wu et al., 2023; Wang et al., 2025). In general, the rational application of NPK inorganic fertilizers is linked not only to an increase in soil aggregate stability but also to an increase in the carbon content within the aggregates (Ogunwole, 2008; Gautam et al., 2022). Phosphorus application has a significant influence on aggregates. For example, Chen Z. et al. (2024) demonstrated that long-term phosphorus fertilizer application significantly increased the number of macroaggregates and aggregates stability. The increase in aggregate stability was related to the formation of organic-calcium complexes, which result in the consecutive sequestration of SOC through soil aggregates. Moreover, nitrogen application has been demonstrated by Su et al. (2024) to have an impact on SOC transformation within soil aggregates. Moreover, they reported that ammonium or nitrate fertilizers play different roles in the SOC associated with soil aggregates. While nitrate fertilizer had a greater inhibitory effect on labile SOC degradation, ammonium application substantially inhibited recalcitrant SOC degradation.

The combined application of organic and mineral fertilizers leads to greater improvements in aggregate stability, with a more pronounced stabilisation of carbon within the aggregates than when either type of fertilizer alone (organic or mineral) is used. For example, Mao et al. (2024) reported that applying mineral fertilizers combined with OM (cattle manure, rice straw, and green manure) over a 12-year period in paddy soils resulted in the greatest increase in SOC within aggregates, particularly in MAOC. These findings suggest that using an appropriate organic/inorganic fertilizer ratio could not only improve soil health but also help capture and stabilise carbon in agricultural soils. A meta-analysis by Yang X. et al. (2024) revealed that combining inorganic and organic fertilizers increased aggregate-associated SOC for all aggregate sizes in uplands, whereas a contrasting result was observed in clay loam soil, demonstrating the effects of factors such as climate, texture, pH and the type of fertilizer. Moreover, combine chemical and organic fertilizer improve nutrient fixation (Okebalama and Marschner, 2023),

TABLE 1 Comparison of the main tillage systems.

Feature	Conventional tillage	Minimum tillage	No tillage (zero tillage)
Soil disturbance	High (deep and complete inversion)	Moderate (shallower and partial disturbance)	Very low or none (soil left undisturbed)
Typical depth	>20 cm	<15 cm (often 5–10 cm)	None
Tools used	Mouldboard plough, disc plough	Chisel plough, disc harrow, rotary tiller	Seed drill or direct seeder
Crop residue management	Buried	Partially retained on surface	Retained fully on surface
Energy and labour input	High (more passes and fuel)	Moderate	Low (fewer passes, less fuel)

microorganisms' communities in soil aggregates (Feng et al., 2022) and heavy metal fixation (Liu et al., 2023).

In summary, the choice of the fertilization regime deeply influences soil aggregation and the related environmental and ecological functions.

4.3 Tillage intensity

The relationship between tillage intensity, soil aggregate dynamics and carbon associated with soil aggregates is essential for understanding how soil management affects soil structure and carbon sequestration. In practice, this is illustrated by three types of approach: conventional tillage, minimum tillage and no-till. The characteristics of each of these techniques are presented in Table 1. However, it is important to highlight the recent concerns regarding the influence of tillage on soil aggregates and their carbon sequestration potential.

4.3.1 Conventional tillage

Traditional farming methods that include significant soil disturbance are referred to as conventional tillage or intensive tillage. Convectional tillage includes numerous passes of tillage machinery to prepare the seedbed, weeds, and incorporate crop residues. These numerous operations affect not only the topsoil, but also the subsoil layer (Kalaiselvi et al., 2023). Conventional ploughing, notably deep ploughing, disrupts the stability of soil aggregates, particularly macroaggregates, causing their accelerated breakdown. This process results in the loss of SOM, which acts as the principal binder for macroaggregates via mechanisms such as root mucilage and enmeshment (Oades, 1984; Tisdall and Oades, 1982). Thus, conventional tillage practices result in significant decrease of the macroaggregate fraction and increase of the microaggregate fraction (Devine et al., 2014; Jat et al., 2019). Furthermore, the reduction in macroaggregate stability, which offers protection to the soil microaggregates, increases the soil's vulnerability to wind or water erosion and, consequently, the loss of the carbon they store (Weidhuner et al., 2021; Cui et al., 2022). However, deep ploughing in arid regions, although linked to a deterioration in soil structure, could encourage a transfer of SOC from the surface layer (topsoil, 0–20 cm) to the subsoil, 20–50 cm (Feng et al., 2020). This can be explained by the low level of rainfall, which reduces sensitivity to water erosion.

4.3.2 Minimum tillage

It is important to clarify that there is considerable confusion between "Reduced tillage", "Minimum tillage", and even "No tillage" depending on the author. However, within the scope of this work, and as shown in Table 2, Minimum tillage refers to a set of farming practices designed to reduce the intensity of soil disturbance compared with conventional ploughing, while ensuring a certain amount of soil preparation for planting. The aim is not to avoid disturbing the soil altogether, but to work it less deeply, more purposefully or less frequently. It has been shown that reducing tillage not only improves agricultural production but also prevents soil degradation (Busari et al., 2015). But it also reduces emissions of greenhouse gases (Saldukaitė et al., 2022). Most of the minimum tillage techniques have been demonstrated to increase large macroaggregates (>2 mm) proportion and aggregates stability in comparison to conventional tillage (Kasper et al., 2009; Gao et al., 2022). The increase in the large macroaggregate fraction is associated with an increase in SOC storage in this aggregate fraction (Liu D. et al., 2025).

This can be explained not only by the long-term stabilisation of the SOC within the microaggregates occluded inside the stable macroaggregates. But also, by the action of the labile SOC resulting from the activity of the roots and microorganisms, which acts as a binder within the macro-aggregates of the soil. This accumulation of SOC is promoted by the reduction in environmental disturbance caused by multiple ploughings in the conventional system (Zhang et al., 2013; Sae-Tun et al., 2022).

Moreover, techniques such as rotary tillage and ridge tillage increase the proportion of large macroaggregates, and the SOC associated with these aggregates down to a depth of 30 cm, which promotes carbon sequestration not only in the topsoil (0–20 cm), but also in the subsoil (Zibilske and Bradford, 2007; Wang B. et al., 2019).

4.3.3 Zero- or no-tillage

In general, no tillage is considered to be the best conservative farm management practice, increasing soil aggregation due to the very low level of soil disturbance (Du et al., 2022). Compared with minimum tillage, no tillage results in greater development of the microorganism community, which contributes to higher SOC sequestration in the large macroaggregates (Lu et al., 2018; Jayaraman et al., 2022). However, it has been shown that the improvement in macroaggregates and the resulting sequestration of SOC in no tillage practices is limited solely to the topsoil (Singh et al., 2014; Wang H. et al., 2019). In fact, if ploughing is associated with the breakdown of soil macroaggregates, it allows the soil to be inverted, allowing OM to be buried and, by extension, soil microorganisms to colonise the soil at depth, which explains the improvement observed in the subsoil with rotary tillage or ridge tillage.

TABLE 2 Minimum tillage techniques.

Technique	Description
Shallow stubble cultivation	Very shallow working of the topsoil (5–10 cm) after harvest
Chisel ploughing	Uses tines to loosen soil without inverting it completely
Rotary tillage	Uses rotating blades to mix the surface layer (usually <15 cm deep)
Strip tillage	Soil is worked only in narrow bands where seeds will be planted
Disc harrows or tine cultivators	Break up surface crust without turning the whole soil profile
Ridge tillage	Crops are planted on raised ridges formed and maintained with minimal tillage

TABLE 3 Tillage intensity effects on aggregates and aggregates-associated SOC.

Tillage system	Aggregate size distribution		Aggregate stability	SOC distribution	SOC protection
	Macro (>2 mm)	Micro (<0.25 mm)			
Conventional Tillage	Decrease	Increase (free)	Low	Loss of SOC due to oxidation and erosion; Weak association with aggregates	Weak macroaggregates disrupted, SOM exposed to decomposition
Minimum Tillage	Increase	Increase (occluded)	Medium to high	SOC increasingly stabilised within macroaggregates and occluded microaggregates	Moderate to strong: Favourable to C storage across topsoil and subsoil
No Tillage	Increase	Increase (occluded)	High	High SOC accumulation in macroaggregates at the surface; Less mixing, but strong microbial-driven aggregation	Strong But benefits mostly limited to topsoil unless combined with residue management

While this section highlights the impact of tillage systems on soil aggregation and associated SOC fractions, due to the extensive literature available, other environmental and ecosystem functions of soil aggregates are also influenced by tillage intensity. No-tillage is linked to improved soil fauna and microorganisms compared to tillage management (Wang B. et al., 2019; Sharma and Singh, 2023). Furthermore, it also promotes nutrient fixation in soil aggregates (Li H. et al., 2023). Conversely, minimum tillage has been shown to improve water infiltration compared with other tillage methods (Xu et al., 2024).

In sum, as Table 3 shows, tillage intensity plays a determining role in the stability of soil aggregates and their contribution to carbon sequestration. However, several mechanisms and aspects should be better explored, including the effects of incorporating organic amendments (e.g., compost, biochar) in minimum or no-tillage systems on SOC retention in aggregates. The trade-offs between surface and subsoil SOC accumulation should also be better estimated.

5 Future research into the dynamics of aggregates and their potentials for ecosystem services delivery

Soil health is vital for sustainable agricultural production in the context of climate change and environmental issues. This review has shown that soil aggregates are associated with major environmental and ecosystem functions. A quantification of the impacts of environmental stressors (globally linked to land use) on soil aggregates could provide measurable indicators and allow the conversion of scientific information into practical suggestions for decision makers, farmers and other stakeholders to improve the overall soil health and environmental sustainability.

The combination of developing technologies, such as remote sensing, isotopic analysis, and molecular approaches, is expected to transform the assessment of soil attributes at various scales. These technologies could be used to monitor the spatial distribution and temporal evolution of soil aggregates, allowing for more accurate assessments of soil health. Such multi-scale analysis could help identify sustainable land management strategies that increase soil aggregation and environmental and ecosystem functions. Such investigations will most likely focus on strategies for increasing SOM content, minimizing soil erosion, and promoting biodiversity. Long-term monitoring studies are critical for tracking changes in soil quality over time and determining the effectiveness of land management strategies.

Several recent studies have shown that soil inorganic carbon (SIC) predominates in soils in arid environments (Naorem et al., 2022). This fraction of soil carbon results from the fixation of carbon dioxide in the soil by calcium ions derived from the weathering of rocks. SIC represents a significant and underestimated potential for carbon dioxide sequestration in the soil (Dina Ebouel et al., 2024). It is generally represented in the soil by the accumulation of calcium carbonate ($CaCO_3$). Pihlap et al. (2021) have established that this calcium carbonate controls the initial stages of microaggregate formation in loessic calcareous soils. However, the stability of this carbon fraction remains poorly understood. Furthermore, SIC associated with soil aggregates could not only constitute a serious indicator of soil health in arid environments, but also a reliable solution for combating climate change in these environments.

6 Conclusion

Understanding the mechanisms by which soil aggregates are formed and the factors that influence their stability and their ecological and environmental functions is necessary to support sustainable land management practices that maintain soil health. This study highlights that soil aggregates control key environmental and ecosystem functions within the soil, including: the regulation of microorganism communities and their interactions; the SOC storage; the adsorption-desorption of nutrients and heavy metals; and the movement of water. Nevertheless, land use and changes in land use significantly shape the intervention of soil aggregates in these functions. Sustainable land use practices or natural ecosystems promote soil aggregation, thereby facilitating the positive control of aggregates on environmental and ecosystem functions. Conversely, improper farming practices disrupt soil aggregates, exacerbating environmental issues and ecological disturbance. These findings lends credence to the essential roles of aggregates in maintaining soil health, enhancing carbon sequestration and supporting sustainable agricultural and environmental practices. However, knowledge of the soil inorganic carbon associated with aggregates has been neglected, as inorganic carbon constitutes the main fraction of the soil carbon in arid areas. Large-scale analysis and modelling could also help to better explain the interaction and predict evolution.

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