# CARBONO EDÁFICO: O ELO PARA O EQUILÍBRIO CLIMÁTICO E A SEGURANÇA ALIMENTAR

# EDAPHIC CARBON: THE NEXUS TO CLIMATE STABILITY AND FOOD SECURITY

# CARBONO EDÁFICO: EL XEXO PARA EL EQUILIBRIO CLIMÁTICO Y LA SEGURIDAD ALIMENTARIA

https://doi.org/10.56238/sevened2025.021-049

Anna Hoffmann Oliveira[1], Gustavo Klinke Neto[2] and Manoela Hoffmann Oliveira[3]


## RESUMO

O presente trabalho aborda a crítica alteração do ciclo global do carbono, um pilar da homeostase planetária, intensificada pelas atividades humanas desde a era industrial. Nesse contexto, a pedosfera desponta como um reservatório de carbono de singular magnitude, cuja saúde é vital para a fertilidade do solo, a resiliência dos ecossistemas, a segurança alimentar e a modulação climática global. A capacidade do solo de sequestrar carbono atmosférico representa, assim, uma via promissora para a mitigação das mudanças climáticas. O objetivo principal é investigar as interações multifacetadas entre o carbono do solo, as mudanças climáticas e as atividades humanas, buscando, através da análise de literatura científica recente publicada em fontes conceituadas, identificar ações que promovam a resiliência dos agroecossistemas e a mitigação das emissões de gases de efeito estufa. As principais considerações indicam que, embora o solo seja um vasto reservatório de carbono orgânico (COS) e inorgânico (CIS), práticas insustentáveis como desmatamento, aração intensiva e manejo inadequado o convertem de sumidouro em fonte de emissões. Projeções climáticas apontam para a exacerbação dessas pressões. Contudo, a adoção de práticas como agricultura conservacionista, sistemas agroflorestais, uso de biochar e restauração de ecossistemas degradados pode significativamente aumentar o COS, melhorar a saúde edáfica e reduzir emissões. Iniciativas globais como RECSOIL e nacionais como o Plano ABC+ exemplificam esforços para reverter essa tendência e promover uma gestão do solo climaticamente inteligente e regenerativa, embora persistam desafios na quantificação, monitoramento e superação de barreiras socioeconômicas.


**Palavras-chave:** Pedosfera. Aquecimento Global. Agroecossistemas. Matéria Orgânica do Solo.

[1]Prof. Dr.
Dr. in Soil Science
Federal University of São Carlos – Center for Agrarian Sciences (CCA-UFSCar)
E-mail: annahoffmann@ufscar.br
ORCID: https://orcid.org/0000-0002-5479-8359
[2]Doctorate student in Geography
State University of Campinas – Institute of Geosciences
E-mail: gus.klinke@@gmail.com
ORCID: https://orcid.org/0000-0002-5876-7138
[3]Dr.  in Social Sciences.
University of São Paulo, USP, Brazil.
E-mail: manoela.hoffmann@gmail.com
ORCID: https://orcid.org/0000-0002-3372-6751

## ABSTRACT

This study addresses the critical alteration of the global carbon cycle, a cornerstone of planetary homeostasis, intensified by anthropogenic activities since the Industrial Revolution. Within this context, the pedosphere emerges as a carbon reservoir of significant magnitude, its integrity being crucial for soil fertility, ecosystem resilience, food security, and global climate regulation. Consequently, the soil's capacity to sequester atmospheric carbon represents a promising avenue for climate change mitigation. The primary objective is to investigate the multifaceted interactions among soil carbon, climate change, and human activities. This is achieved through an analysis of recent scientific literature from peer-reviewed sources, aiming to identify strategies that enhance agroecosystem resilience and mitigate greenhouse gas emissions. Principal findings indicate that, while the soil constitutes a vast reservoir of both soil organic carbon (SOC) and soil inorganic carbon (SIC), unsustainable practices—including deforestation, intensive tillage, and improper management—convert it from a carbon sink to an emission source. Climate projections suggest an exacerbation of these pressures. Nevertheless, the adoption of practices such as conservation agriculture, agroforestry systems, biochar application, and the restoration of degraded ecosystems can significantly augment SOC, improve edaphic health, and reduce emissions. Global initiatives, such as RECSOIL, and national policies, like Brazil's ABC+ Plan, exemplify efforts to reverse this trend and promote climate-smart, regenerative soil management. However, challenges persist in quantification, monitoring, and overcoming socioeconomic barriers to widespread implementation.



**Keywords:** Pedosphere. Global Warming. Agroecosystems. Soil Organic Matter.



## RESUMEN

Este estudio aborda la alteración crítica del ciclo global del carbono, un pilar de la homeostasis planetaria, intensificada por las actividades antropogénicas desde la Revolución Industrial. En este contexto, la pedosfera emerge como un reservorio de carbono de magnitud singular, cuya integridad es crucial para la fertilidad del suelo, la resiliencia de los ecosistemas, la seguridad alimentaria y la modulación climática global. Por consiguiente, la capacidad del suelo para secuestrar carbono atmosférico representa una vía prometedora para la mitigación del cambio climático. El objetivo principal es investigar las interacciones multifacéticas entre el carbono del suelo, el cambio climático y las actividades humanas, mediante el análisis de la literatura científica reciente publicada en fuentes revisadas por pares, con el fin de identificar acciones que promuevan la resiliencia de los agroecosistemas y la mitigación de las emisiones de gases de efecto invernadero. Los principales hallazgos indican que, si bien el suelo constituye un vasto reservorio tanto de carbono orgánico del suelo (COS) como de carbono inorgánico del suelo (CIS), prácticas insostenibles como la deforestación, la labranza intensiva y el manejo inadecuado lo convierten de sumidero en fuente de emisiones. Las proyecciones climáticas apuntan a una exacerbación de estas presiones. No obstante, la adopción de prácticas como la agricultura de conservación, los sistemas agroforestales, el uso de biochar y la restauración de ecosistemas degradados puede aumentar significativamente el COS, mejorar la salud edáfica y reducir las emisiones. Iniciativas globales como RECSOIL y nacionales como el Plan ABC+ ejemplifican los esfuerzos para revertir esta tendencia y promover una gestión del suelo climáticamente inteligente y regenerativa, aunque persisten desafíos en la cuantificación, el monitoreo y la superación de barreras socioeconómicas.



**Palabras clave:** Pedosfera. Calentamiento Global. Agroecosistemas. Materia Orgánica del Suelo.

## INTRODUCTION

The global carbon cycle, a fundamental pillar of planetary homeostasis, has been profoundly altered by the intensification of human activities, particularly since the advent of the industrial age. The increasing atmospheric concentration of carbon dioxide, the main driver of global warming, is a direct consequence of the burning of fossil fuels and, equally significantly, of transformations in land use (IPCC, 2023). The conversion of natural ecosystems for agricultural purposes and the adoption of unsustainable management practices have historically released vast amounts of previously stored carbon, disturbing millennia-old biogeochemical balances and compromising the Earth system's ability to regulate its own temperature (LAL, 2023). This scenario imposes an urgent reassessment of the role of different terrestrial compartments in the carbon cycle, with an emphasis on their dynamics under the pressure of climate change.

From this perspective, the pedosphere emerges as a carbon reservoir of singular magnitude, considerably surpassing the stocks present in plant biomass and in the atmosphere itself. Soil organic carbon (SOC) not only underpins the fertility and resilience of terrestrial ecosystems, directly influencing agricultural productivity and food security, but also plays a central role in modulating the global climate. Thus, the soil's ability to sequester and stabilize atmospheric carbon represents a promising avenue for climate change mitigation. However, this vital function is intrinsically linked to soil integrity, which in turn is strongly influenced by the management practices adopted and the current environmental conditions, making it imperative to deepen knowledge about its dynamics (OLIVEIRA et al., 2023).

Soil degradation, driven by deforestation, intensive plowing practices, and inadequate nutrient management, accelerates the mineralization of organic matter, converting soil from a sink into a net source of greenhouse gases (SHAO et al., 2023). This process not only contributes to global warming, but also compromises soil quality, reducing its capacity for water retention, nutrient cycling, and biodiversity support (AZEVEDO et al., 2024). The consequences extend beyond the climate sphere, affecting the sustainability of production systems and the provision of essential ecosystem services, highlighting the interconnection between soil health, food security, and climate stability (SHEN; TENG, 2023).

Climate projections for the twenty-first century point to an exacerbation of pressures on SOC stocks (NAZIR et al., 2024; SHAO et al., 2023). Given the complexity and urgency of the topic, this work aims to address the multifaceted interactions between soil carbon, climate change and human activities. It also seeks, through the analysis of recent scientific literature, to investigate actions that promote the resilience of agroecosystems and the mitigation of emissions.

## THE GLOBAL CARBON BALANCE

The balance of the carbon cycle is dynamic, maintained when carbon sequestration rates by terrestrial ecosystems equal emission rates, but it is sensitive to disturbances. The displacement of carbon from one reservoir, driven by any change in the cycle, carries more carbon into the other reservoirs. In this way, events that cause greater emission of carbon gases into the atmosphere result in higher temperatures on Earth.

The cyclical flow of carbon between the reservoirs of the Earth system has both slow and fast components. In the slow cycle, carbon takes between 100 and 200 million years to move between rocks, soil, ocean, and atmosphere. In the rapid cycle, about 1015 to 1017 grams (1 to 100 Gt; 1 Gt = 1015 g) of carbon moves each year through life forms on Earth, or biosphere (RIEBEEK, 2011). Because it contains most of the surrounding carbon on the planet, the amount of carbon in the biosphere is of great importance, even though it is a small reservoir (about 2000 Gt) when compared to what is found in the lithosphere (greater than 75,000 Gt), in the oceans (38,400 Gt) and in fossils (4,130 Gt) (MOREIRA; SIQUEIRA, 2006).

Fundamental biological processes such as photosynthesis and respiration stimulate the terrestrial carbon cycle (SHAO et al., 2023). Before reaching the ocean sediments, where it accumulates in the deeper layers, mainly in inorganic forms, carbon circulates through the components of the biosphere. Plants remove carbon dioxide ($CO_2$) from the atmosphere, incorporating it into their biomass. Part of this carbon is transferred to the soil through litter deposition, root exudates, and decomposition of plant residues, forming soil organic matter (SOM), a vast carbon reservoir (LAL, 2023). Soil respiration, carried out by microorganisms and roots, returns $CO_2$ to the atmosphere (CHAPLOT; SMITH, 2023).

Gases such as carbon dioxide ($CO_2$) and methane ($CH_4$) are components of the atmosphere capable of absorbing and emitting radiation at specific wavelengths of the infrared spectrum. This radiation is partly reflected by the Earth's surface, the atmosphere and the clouds and partly retained. Atmospheric gases trap a significant portion of this radiation, returning some of it to space and resulting in a net energy-trapping effect. This phenomenon, called the greenhouse effect, tends to increase the temperature of the planet's surface. Without greenhouse gases (GHG), the Earth would have an average temperature about 33°C lower than the current one, probably frozen (CERRI et al., 2023).

The carbon cycle is, therefore, a fundamental process for the planet's climate regulation, enabling favorable conditions for the evolution of life.

Globally, soils represent the largest reservoir of terrestrial carbon, storing between 1500 and 2400 Gt of carbon in the first meter, significantly more than the carbon contained in vegetation and atmosphere combined (PARAMESHA et al., 2025). This terrestrial reservoir contains approximately three times more carbon than the atmosphere and four times more than vegetation (OLIVEIRA et al., 2023; TONUCCI et al., 2023). The atmosphere, although a smaller reservoir in terms of total stock, is significant due to the direct impact of GHG concentrations on the global climate (NAZIR et al., 2024). On the other hand, soil, a considerable carbon reservoir and decisive for climate balance, has its stocks under continuous threat (AZEVEDO et al., 2024).

## SOIL CARBON

Soil carbon is recognized as indispensable to the functioning and maintenance of its sustainability for food production, in addition to acting as a major carbon sink that can mitigate climate change (SHARIFIFAR et al, 2023). The ability of soil to sequester carbon is influenced by soil type, climate, management, and vegetation (YEASMIN et al., 2023). The balance between carbon input (waste, exudates) and output (respiration, erosion) determines whether the soil is a source or a sink.

In soil, carbon exists in different compartments, with different cycling rates and stability, distinguishing between soil inorganic carbon (CIS) and soil organic carbon (SOC) (LAL, 2023). The amount of CIS and COS stocks up to 2 m of soil is comparable (Zamanian et al., 2021). Estimates point to between 700 and more than 1,000 Gt of CIS (BATJES, 2014) and approximately 1550 Gt referring to COS (SIDDIQUE et al., 2024; GONÇALVES et al., 2025). These amounts exceed the atmosphere (~760 GtC) and terrestrial biomass (~560 GtC) (FU et al., 2023; ZHUANG et al., 2023).

SOC is a heterogeneous complex derived from the decomposition of organic waste and microbial activity, subdivided into labile (active, e.g., dissolved organic carbon, microbial biomass), particulate (intermediate, particulate MOS), and passive (stable, protected, mineral-associated SOM) fractions (LAL, 2023; YEASMIN et al., 2023). The CIS is composed mainly of carbonates, subdivided into lithogenic carbonates, referring to carbonates inherited from materials of limestone origin; biogenic carbonates, formed in terrestrial animals and plants as part of their skeleton; and pedogenic carbonates, formed in the soil by weathering processes, either by dissolution and reprecipitation of pedogenic, lithogenic and biogenic carbonates, or by Ca2+ precipitation from silicate and bicarbonate

(HCO3-) weathering from the root and microbial respiration in alkaline soils (SHARIFIFAR et al, 2023).

The average time that much of the SOC remains in the soil until it is mineralized and released as CO2 into the atmosphere (residence time) is relatively short, from days to years, while the residence time of the CIS under natural conditions is long, on the scale of millennia (SHARIFIFAR et al, 2023). Globally, direct anthropogenic influence (such as agricultural practices and fertilization) affects both the dwell time of COS and CIS (SHARIFIFAR et al, 2023), the latter can be reduced to years or decades (KIM et al., 2020).

Annual CIS losses due to fertilization are estimated at 7.5 Gt, while lime application in liming reaches 273 Gt (ZAMANIAN et al., 2021). CIS losses are irreversible, that is, there is no expected equilibrium when fertilization is applied (RAZA et al., 2021). For COS, soil degradation is often associated with a decrease in carbon stock in this compartment (LI et al., 2025), in the order of 1.93 Gt, attributed to changes in land cover (PADARIAN et al., 2021). Fortunately, COS inventories can be increased through better management. SOC sequestration thus represents a proven and economically viable natural climate change mitigation strategy, with several associated benefits (SHARIFIFAR et al, 2023).

SOC improves aggregation and structural stability, water holding capacity and aeration, and reduces susceptibility to erosion (MA; JIANG, 2025). Chemically, it increases cation exchange capacity (CEC), acts as a pH buffer, and is a source of nutrients (WANG et al., 2024). Biologically, it serves as an energy source for microbial biomass (MA; JIANG, 2025). Thus, SOC influences the physical, chemical, and biological properties of the soil (PARAMESHA et al., 2025; AZEVEDO et al., 2024), being considered the main component of soil health, that is, related to its ability to sustain productivity, diversity, and environmental services (SHEN; TENG, 2023; SONG et al., 2025).

## LAND USE AND INTENSIFICATION OF THE CLIMATE CRISIS

The increase in greenhouse gas emissions, predominantly caused by increasing industrialization and urbanization, has intensified global warming and caused significant changes in weather patterns, including changes in precipitation patterns, with a greater frequency of intense rainfall and extreme weather events (ZHENG et al., 2021). The Intergovernmental Panel on Climate Change (IPCC) unequivocally confirms the human influence on the warming of the atmosphere, oceans and continental territories, of approximately 1.0 °C above pre-industrial levels (IPCC, 2023; XU et al., 2024). During the second half of the twentieth century, an average increase of 0.6°C in global temperature was recorded, evidencing the warming of the planet.

The history of climate change is intrinsically linked to the Industrial Revolution, when the intensive use of fossil fuels initiated an exponential increase in $CO_2$ emissions. Subsequently, agricultural expansion and land-use changes exacerbated this problem. Since the Industrial Revolution, human activities have emitted significant amounts of GHG, resulting in an approximately 50% increase in atmospheric $CO_2$ concentration compared to pre-industrial levels (FRONZA et al., 2024).

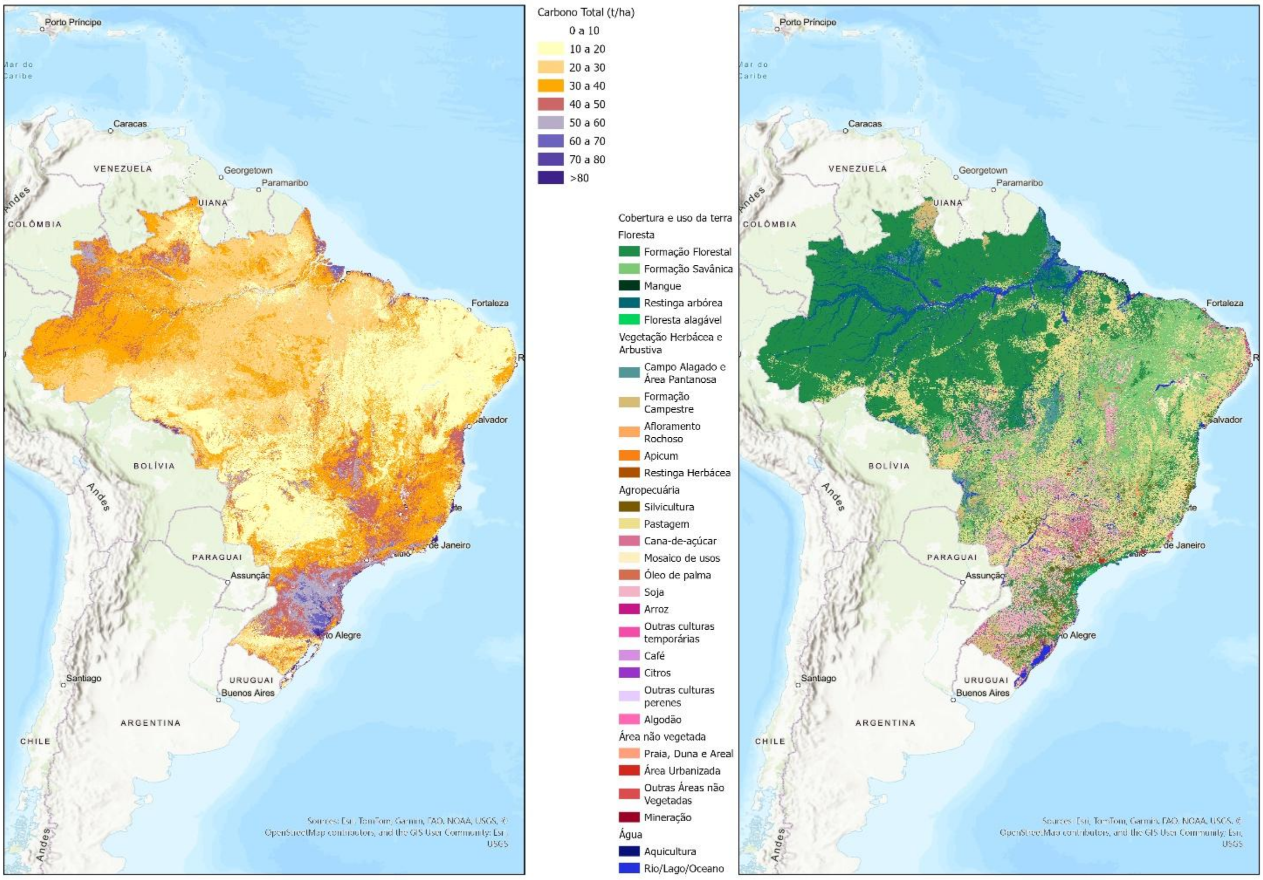
Deforestation, biomass burning, agriculture, and conversions of native ecosystems to agrosystems, along with global warming, profoundly affect the C cycle (SHAO et al., 2023). The change in the balance between sequestration and emissions from these human activities has historically disturbed this balance, leading to the loss of SOM and contributing to a significant portion of GHG emissions across the planet (TABOADA et al., 2021; LAL, 2023; CHAPLOT; SMITH, 2023; RIBEIRO et al., 2023; NAZIR et al., 2024). Specifically, about 21% of anthropogenic $CO_2$ emissions are attributed to the Agriculture, Forestry, and Other Land Use sector (CHOWDHURI; PAL, 2025). A significant source of these gases, agriculture (LAL, 2023) also contributes to $CH_4$ emissions (e.g., enteric fermentation and flooded rice cultivation) and $N_2O$ (e.g., use of nitrogen fertilizers and decomposition of organic waste).

In Brazil, the conversion of native vegetation (Amazon, Cerrado, Caatinga) for agricultural use has led to significant losses of soil carbon (OLIVEIRA et al., 2023; TONUCCI et al., 2023), and approximately 75% of the country's gross emissions ($tCO_2e$ - tons of carbon equivalent) come from the agricultural and land use sectors (IPCC, 2023; FRONZA et al., 2024). In the period from 2019 to 2024 alone, 9,880,551 hectares were deforested, 33% of which were outside the Legal Amazon region. In 2024, according to the Annual Deforestation Report (MapBiomas, 2025), despite the 32.4% reduction in deforestation in all biomes, the Cerrado was the most deforested ecosystem, with 652,197 hectares, concentrated mainly (75%) in the Matopiba region (acronym for Maranhão, Tocantins, Piauí and Bahia). In the Legal Amazon region, 377,708 hectares were deforested, making it the second most deforested biome.

The most recent annual survey, from 2023, presents the estimated panorama for land use and cover (MapBiomas, 2024a) and for SOC in the 0-30 cm layer (MapBiomas, 2024b), observed in Figure 1. The data indicate that 66.72% of the national territory is under natural cover and anthropic use accounts for 33.06%, with 32.52% attributed to agriculture (Figure 1). SOC stocks in the ranges of 40 to 50 t/ha (42.15%) and 30 to 40 t/ha (34%) cover a large part of Brazil, concentrated in the north, south and southeast regions

(Figure 1). Approximately 23% of the total area has stocks above 50 t/ha, concentrated mainly in the southern region.

Figure 1. Distribution of total organic carbon stock in the 0-30 cm layer and land use and land cover, relative to the year 2023, in Brazil (Source: Mapbiomas, 2024a and b).




Prepared by the authors.

In Europe, intensive practices in agriculture represent a historical carbon debt (PETERSSON et al., 2025). Conventional tillage in agriculture, for example, exposes SOM to oxidation, accelerating its decomposition and $CO_2$ emission, being a significant factor in the loss of SOM (CHAPLOT; SMITH, 2023). In addition, the export of nutrients by crops without adequate replacement can lead to the "mining" of SOM, contributing to the loss of soil carbon (CHAPLOT; SMITH, 2023). However, as pointed out by Efthimiou (2025), soil degradation remains a significant threat, with 60-70% of the European Union's soils in an unhealthy state, exacerbating carbon loss to the atmosphere.

## CLIMATE PROJECTIONS: CHALLENGES AND TARGETS

Climate models project a future with higher global average temperatures, changes in precipitation patterns, and an increase in the frequency and intensity of extreme weather events (TABOADA et al., 2021; CHOWDHURI; PAL, 2025; NAZIR et al., 2024). The consequences include reduced water availability, rising sea levels, loss of biodiversity, impacts on human health, and threats to food production, which can lead to desertification and loss of arable land (LI et al., 2025). Shao et al. (2023) warn that the C budget of forests and the dynamics of C in the soil will be altered, with the potential to turn sinks into sources.

In response, the Paris Agreement (COP 21, 2015) has emerged as the main multilateral policy instrument, aiming to limit global warming to well below 2°C, preferably to 1.5°C, above pre-industrial levels. The document highlights the gap between current commitments and the ambition needed, calling for emissions reductions of 43% by 2030 or 69% by 2040 compared to 2019. Corroborating this mismatch, the analysis of ice core samples from Antarctica revealed that, in 2023, global warming caused by human activities reached 1.49°C above pre-industrial levels (JARVIS; FORSTER, 2024). CO2 levels increased by 142 ppm compared to the period before 1700, confirming that human impact on the climate raised the temperature by 1.49°C (JARVIS; FORSTER, 2024). Progressively, the year 2024 marked the violation of the Paris Agreement for the first time, that is, there was an average global warming above 1.5 °C compared to the pre-industrial period in all months (BEVACQUA et al., 2025).

To articulate a prospective analysis of the significance of isolated warm years in relation to the long-term goals of the Paris Agreement, Bevacqua et al. (2025) investigated the probability that a single year indicates the imminent or concomitant entry into the 20-year period whose average warming will reach this same threshold. This threshold is relevant because the IPCC uses 20-year averages to assess human-induced global warming and associated climate risks. The authors indicated that for warming levels already reached (0.6 °C to 1.0 °C), the first singular year to exceed these thresholds consistently occurred within the first 20-year period in which the average temperature reached the same values. Consequently, the 2024 record signals that the Earth has probably already entered a 20-year period with average warming of 1.5°C and indicates that the warming trend above 1.5°C is long-term, implying that the climate impacts associated with this level of warming may begin to emerge.

The longevity of sequestered C under different climatic and management scenarios is uncertain. The impact of rising temperatures and water change on the decomposition and stability of sequestered SOC needs to be better understood (KONG et al., 2025; XU et al., 2024). There is a dimension of sensitivity of tropical ecosystems to temperature increases and reductions in precipitation that impact the effective moisture of the ecosystem (SOUZA et al., 2021) and affect the structure and activity of soil biological communities (AZEVEDO et al., 2024), determinants of carbon cycles. Climate change, especially warming, can accelerate the decomposition of SOM, releasing $CO_2$ (SHAO et al., 2023; QIU et al., 2023), and affect microbial metabolism by influencing C and N cycling (SHAO et al., 2023). Thus, global warming also directly affects the biogeochemical processes of the soil.

Xu et al. (2024) demonstrated that experimental heating altered the N:P ratios of soil and P for microorganisms and plants. In the alpine steppe of the Tibetan Plateau, increased temperature, although correlated with increased COS stock, also led to increased soil respiration (ZHAO et al., 2025). Also, changes in precipitation affect soil moisture, a key controller of microbial activity (WANG et al., 2013). The average residence time of carbon in tropical ecosystems (vegetation and soil combined) can be less than 20 years, making it absolutely necessary to assess the impacts of environmental changes on these stocks (SOUZA et al., 2021). The importance of accurately quantifying SOC stocks is evident, but there are still uncertainties that make it difficult to predict carbon-climate responses (FLYNN et al., 2024; LIN et al., 2024).

The agricultural sector stands out as one of the most affected by the effects of global warming. Agricultural production, essential for food security, has significant carbon and water footprints that tend to be exacerbated by climate change (NAYAK et al., 2023) and also to exhibit great spatial variability (TABOADA et al., 2021). Simulations indicate temperature increases and variations in precipitation that can lead to substantial losses of COS in monoculture systems, while agroforestry systems may show greater resilience (JIANG et al., 2025; PARAMESHA et al., 2025). In scenarios of reduced precipitation and temperature increases in tropical regions, there is a tendency for COS stocks to decrease, especially in degraded pastures (RIBEIRO et al., 2023).

The conversion of natural ecosystems to conventional agriculture often results in COS losses (PARAMESHA et al., 2025), however, certain practices can reverse this trend. In this context, the climate crisis emerges as one of the greatest and most complex environmental challenges that humanity will have to face in the twenty-first century. Signatory countries to the Paris Agreement must submit the second cycle of their Nationally Determined Contributions (NDCs), which will be in force from 2031 to 2035. These new targets are key to determining whether global warming can be limited to less than 2°C, as provided for in the Paris Agreement, or whether it will be possible to achieve the more ambitious goal of 1.5°C [this is no longer possible according to current emission levels], reinforced by the COP28 Global Stocktake in 2023. To do so, global emissions need to fall by 60% by 2035 compared to 2019, with a cut of at least 42% by 2030. However, current NDCs, if fully implemented, would result in a reduction of only 5.9% by 2030, highlighting the need for greater ambition in climate action (IPCC, 2023).

Brazil, as the host of COP30 in 2025, has committed to being one of the first countries to present its new NDC. Currently, the country has absolute emission reduction targets of 48% by 2025 and 53% by 2030, compared to 2005 levels. The new NDC will be based on mitigation trajectories of the Climate Mitigation Plan, aiming to achieve zero net emissions by 2050 (BRASIL, 2025). The Climate Observatory (2024) proposed a more ambitious NDC, suggesting that Brazil reach net emissions of 400 million tons of $CO_2$ by 2030 and 200 million by 2035, which would require zeroing deforestation and expanding actions in sectors such as energy, agriculture, and waste.

## THE CLIMATE SOLUTION IN AGRICULTURE

The global stock of soil carbon stored in agricultural areas is estimated to be around 12%, equivalent to 12.6% of the planet's land area (CERRI et al., 2023). Considering the importance of SOC and the impacts of climate change and land use on its stocks, proper soil management is a powerful tool for its increase (LAL, 2023; SHAO et al., 2023; SONG et al., 2025). Conservation agriculture is climate-smart: it provides for minimal soil disturbance (reduced tillage, no-tillage), crop rotation, cover crops, organic fertilization, and integrated systems (COLUNGA et al., 2025; GONÇALVES et al., 2025; MA; JIANG, 2025; USMAN, 2025; LAL, 2023; CHAPLOT; SMITH, 2023; OLIVEIRA et al., 2023; TABOADA et al., 2023), promoting the increase in SOC. This type of agriculture is also referred to as "carbon farming", which designates the adoption of restorative land uses and best management practices to create a positive C balance, generating additional income (LAL, 2023).

The use of cover crops and green manure add biomass, protect against erosion, improve soil structure, and can fix nitrogen (USMAN, 2025). In addition, the return of crop residues (straw) optimizes productivity and C balance (WANG et al., 2024; NAZIR et al., 2024). In this set of measures, mechanical conservation practices for erosion control, such as terracing and contour cultivation, prevent not only soil loss, but also SOM loss (USMAN, 2025). Edaphic conservation practices, on the other hand, must consider the complexity of the relationship between N, C and GHG emissions (WANG et al., 2024), so that, for the replacement of exported nutrients, organic fertilization (manure, composts) can be chosen, which, in addition to improving fertility, has the benefits of avoiding mineralization and directly increasing the SOM content (CHAPLOT; SMITH, 2023; USMAN, 2025; SIDDIQUE et al., 2024).

Systems that integrate trees, crops, and/or pastures (agroforestry and agroforestry systems) are often related to the increase in COS. PAN et al. (2025) estimated this rate at 10.7% globally, especially in arid areas. In semi-arid regions, TONUCCI et al. (2023) found an increase in COS and N in depth in agroforestry systems. The conversion of degraded pastures to agroforestry systems in the Cerrado increased the SOC (RIBEIRO et al., 2023; OLIVEIRA et al., 2023). PARAMESHA et al. (2025) showed an increasing trend of COS under climate change conditions in coconut + pineapple intercropping systems.

Other techniques and technologies can be mentioned. Biochar, for example, is a carbonized biomass for agricultural use that, because it is thermally altered, has a much slower decomposition capable of creating a large long-term carbon stock in the soil (REZENDE et al., 2011). Biochar is about 1500 to 2000 times more stable than non-pyrolyzed organic matter and its residence time in the soil is hundreds to thousands of years (REZENDE et al., 2011; QIU et al., 2023).

Precision agriculture optimizes the use of inputs associated with GHG emissions; plant breeding develops crops with deeper root systems that deposit carbon in places where it tends to be less susceptible to rapid decomposition and release into the atmosphere (LAL, 2023); and mycorrhizae and plant growth-promoting microorganisms contribute to the influx and storage of C (AZEVEDO et al., 2024). In addition, the restoration of degraded ecosystems can convert source areas to carbon sinks, as in the case of the recovery of degraded pastures, whose carbon sequestration potential is significant and reach about 2.50 Mg C $ha^{-1}$ $year^{-1}$ for well-managed pastures (FRONZA et al., 2024).

The adoption of carbon agriculture and other practices depends on the integration of socioeconomic, political, cultural, and market factors (EFTHIMIOU, 2025; CHOWDHURI; PAL, 2025). Likewise, predictive modeling needs to be improved and must also be integrated, with biogeochemical, climate, management, and socioeconomic processes converging to generate information on spatial variability and uncertainties associated with the processes of monitoring and analyzing carbon sequestration scenarios (FLYNN et al., 2024; LIN et al., 2024; WANG et al., 2013; PARAMESHA et al., 2025; DOU et al., 2022; REN et al., 2025; JIANG et al., 2025).

Although specific regional data are scarce for areas such as MATOPIBA and semi-arid regions (OLIVEIRA et al., 2023; TONUCCI et al., 2023), it is important to consider the need to optimize and regionalize practices for different agroecosystems (USMAN, 2025; MA; JIANG, 2025). Knowledge of local specificities, combined with farmer engagement, technical support, and incentive policies are inherent to policies and governance focused on the successful implementation of carbon agriculture (USMAN, 2025; LAL, 2023). Good examples are the RECSOIL (Recarbonizing Global Soils) initiative, at the global level, and the Brazilian public policy called Plano ABC (Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture), at the national level.

## THE GLOBAL STRATEGY TO RESTORE SOIL CARBON

RECSOIL (Recarbonizing Global Soils) is a comprehensive initiative whose fundamental goal is to increase SOC stocks on a global scale through the implementation of a diverse set of sustainable land use and management practices. The concept of RECSOIL refers to the effort and objective of improving the health and functionality of soils around the world, making them larger carbon sinks. Led by the Food and Agriculture Organization of the United Nations (FAO/UN) Global Partnership on Soils (GSP) and the Intergovernmental Technical Panel on Soils (ITPS), RECSOIL started in 2017 as a direct response to the need to unlock the potential of SOC for climate change mitigation and adaptation by sequestering CO2, increase the resilience of agricultural systems to climate change (adaptation), increase food security, conserve soil biodiversity and combat soil degradation (FAO; ITPS, 2021).

The result of the collective work and competence of a vast international scientific community resulted in a technical manual on the management of SOC at the national and local scales, including recommendations on the GHG balance and C-N interactions, as well as their adaptations to local contexts. The term recarbonization involves the initiative and process of: 1- reversing the trend of carbon loss, since many soils around the world have lost significant amounts of their original organic carbon due to unsustainable management practices, deforestation and other human activities; 2- increase carbon sequestration by promoting the absorption of CO2 from the atmosphere by plants and its subsequent incorporation and stabilization in the soil in the form of organic matter; and 3- implement sustainable soil management practices with the adoption of various agricultural, forestry, and other ecosystem management techniques (such as pastures, wetlands, and urban soils) that are known to protect existing SOC and/or add new carbon to the soil (FAO; ITPS, 2021). The RECOSOIL manual compiles and details many of these practices for agriculture, pastures, integrated systems, forestry, wetlands, and urban soils.

## THE BRAZILIAN STRATEGY FOR SUSTAINABLE AND CLIMATE-RESILIENT AGRICULTURE

The Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture with a view to sustainable development (2020-2030), called ABC+, represents a strategic public policy in Brazil, aimed at consolidating an agricultural production paradigm that reconciles productivity, climate resilience and environmental sustainability. Its creation was motivated by the growing urgency of climate action, consumer and civil society demands for more sustainable practices, and the need to align Brazilian agriculture with the sustainable development goals (SDGs), notably SDG 2 (Zero Hunger and Sustainable Agriculture) and SDG 13 (Action against global climate change) (BRAZIL, 2021).

The ABC+ Plan succeeds and expands the ABC Plan (Low Carbon Emission Agriculture), implemented between 2010 and 2020, which emerged as a commitment of the Brazilian agricultural sector in the face of the challenges of climate change and national GHG reduction targets. The new cycle, ABC+, aims to expand the advances of the previous decade, incorporating new strategies and improving governance. It is based on three main conceptual bases.

The first is the integrated approach to the landscape, where the management of the agricultural territory is done in a systemic way, integrating the various elements of the rural landscape at its different scales, promoting the efficient use of suitable areas, environmental regularization, the conservation of soil, water and biodiversity, and the appreciation of local specificities. The second is the combination of adaptation and mitigation strategies, which recognizes the need for actions that simultaneously reduce GHG emissions (mitigation) and reduce the vulnerability of production systems to climate impacts, increasing their resilience (adaptation). Finally, the encouragement of the adoption and maintenance of sustainable production systems, practices, products, and processes, whose promotion of scientifically based conservation agricultural technologies and management ensure productive efficiency and profitability, while conserving natural resources and strengthening the resilience of ecosystems (BRASIL, 2021).

Among the strategies of the ABC+ plan is the encouragement of the adoption and maintenance of integrated systems (e.g. Agroforestry and agroforestry), no-tillage, biological nitrogen fixation, planted forests, recovery of degraded pastures and treatment of animal waste. In addition, the socioeconomic dimension is contemplated from the promotion, expansion and diversification of economic, financial and fiscal sources and instruments, including carbon credits and diversified sources of financing; and actions for the transfer and dissemination of technologies, training and technical assistance to expand the reach and quality of technical assistance and rural extension, also using digital technologies (BRASIL, 2021).

## FINAL CONSIDERATIONS

The SOC constitutes a critical component of the global climate system, whose dynamics are intrinsically shaped by both natural processes and anthropogenic interventions. Human activities, notably the conversion of natural landscapes and conventional agriculture, have triggered substantial losses of SOC, transmuting vast areas of sinks into sources of greenhouse gas emissions and, simultaneously, degrading the productive capacity and resilience of soils. Ongoing climate change, with rising temperatures and changing precipitation patterns, exacerbates this vulnerability, threatening to accelerate the mineralization of organic matter and intensify erosive processes, with particularly severe implications for vulnerable and carbon-rich ecosystems, such as tropical forests, peatlands, and permafrost, which can release massive volumes of carbon, creating positive feedback loops that can amplify global warming.

On the other hand, the significant potential of sustainable soil management to address the climate crisis and promote food security is clearly manifested. The adoption of practices such as conservation agriculture, agroforestry systems, crop-livestock-forest integration, and biochar application demonstrate the ability to reverse degradation trends, increase soil carbon sequestration, improve soil health, and reduce net greenhouse gas emissions. Global and national initiatives, such as RECSOIL and the ABC+ Plan in Brazil, reflect a growing recognition of this potentiality. However, there are considerable challenges, including the need for advances in the quantification and monitoring of SOC stocks, overcoming socioeconomic and cultural barriers to the adoption of new practices, and the formulation of effective and integrated public policies that encourage the transition to climate-smart and regenerative soil management.

## ACKNOWLEDGMENT

The authors thank the Center for Agrarian Sciences of UFSCar (CCA) - FAI RTI-CCA project for funding the work.

## REFERENCES


1. Azevedo, L. C. B., Bertini, S. C. B., Ferreira, A. S., Rodovalho, N. S., Ferreira, L. F. R., & Kumar, A. (2024). Microbial contribution to the carbon flux in the soil: A literature review. Revista Brasileira de Ciência do Solo, 48, e0230065. https://doi.org/10.36783/18069657rbcs20230065

2. Batjes, N. H. (2014). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 65(1), 10–21. https://doi.org/10.1111/ejss.12114_2

3. Bevacqua, E., Schleussner, C., & Zscheischler, J. (2025). A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. Nature Climate Change, 15(3), 262–265. https://doi.org/10.1038/s41558-025-02246-9

4. Brasil. Ministério da Agricultura, Pecuária e Abastecimento. (2021). Plano setorial para adaptação à mudança do clima e baixa emissão de carbono na agropecuária com vistas ao desenvolvimento sustentável (2020-2030): Visão estratégica para um novo ciclo. https://www.gov.br/agricultura/pt-br/arquivos/abc_final.pdf

5. Brasil. Ministério do Meio Ambiente e Mudança do Clima. (2025). Rumo à COP30. https://www.gov.br/mma/pt-br/assuntos/mudanca-do-clima/rumo-a-cop-30

6. Cerri, C. E. P., Abbruzzini, T. F., Carvalho, J. L. N., Cherubin, M. R., Frazão, L. A., Maia, S. M. F., & Oliveira, D. M. S. (2023). Matéria orgânica do solo e o equilíbrio global de carbono. In W. Bettiol, C. A. Silva, C. E. P. Cerri, L. Martin-Neto, & C. A. Andrade (Eds.), Entendendo a matéria orgânica do solo em ambientes tropical e subtropical (Vol. 1, pp. 211–254). Embrapa.

7. Chaplot, V., & Smith, P. (2023). Cropping leads to loss of soil organic matter: How can we prevent it? Pedosphere, 33(1), 8–10. https://doi.org/10.1016/j.pedsph.2022.06.002

8. Chowdhuri, I., & Pal, S. C. (2025). Challenges and potential pathways towards sustainable agriculture crop production: A systematic review to achieve sustainable development goals (SDGs). Soil & Tillage Research, 248, 106442. https://doi.org/10.1016/j.still.2024.106442

9. Colunga, S. L., Wahab, L., Fierro Cabo, A., & Pereira, E. (2025). Carbon sequestration through conservation tillage in sandy soils of arid and semi-arid climates: A meta-analysis. Soil & Tillage Research, 245, 106310. https://doi.org/10.1016/j.still.2024.106310

10. Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change. (2015). Meetings. https://www.un.org/sustainabledevelopment/cop21/

11. Dou, X., Wang, X., Wang, J., Zhang, Q., Wang, S., & Li, Z. (2022). Risk assessment of soil erosion in Central Asia under global warming. Catena, 212, 106056. https://doi.org/10.1016/j.catena.2022.106056

12. Efthimiou, N. (2025). Governance and degradation of soil in the EU. An overview of policies with a focus on soil erosion. Soil & Tillage Research, 245, 106308. https://doi.org/10.1016/j.still.2024.106308

13. Flynn, T., Kostecki, R., Rebi, A., & Taqi, R. (2024). Accessing global soil raster images and equal-area splines to estimate soil organic carbon stocks on the regional scale. Pedosphere. https://doi.org/10.1016/j.pedsph.2024.07.004

14. Food and Agriculture Organization of the United Nations (FAO) & Intergovernmental Technical Panel on Soils (ITPS). (2021). Recarbonizing global soils: A technical manual of recommended management practices. Volume 1: Introduction and methodology. FAO. https://doi.org/10.4060/cb6386en

15. Fronza, E. E., Ten Caten, A., Bittencourt, F., Zambiazi, D. C., Schmitt Filho, A. L., Seó, H. L. S., & Loss, A. (2024). Carbon sequestration potential of pastures in Southern Brazil: A systematic review. Revista Brasileira de Ciência do Solo, 48, e0230121. https://doi.org/10.36783/18069657rbcs20230121

16. Fu, Z., Hu, W., Beare, M., Baird, D., & Li, S. (2023). Response of soil organic carbon stock to land use is modulated by soil hydraulic properties. Soil & Tillage Research, 233, 105793. https://doi.org/10.1016/j.still.2023.105793

17. Gonçalves, D. R. P., Canisares, L. P., Wood, H. A. J., Barth, G., Peper, A., Galvan, J., & Anselmi, A. (2025). Agriculture intensification in subtropical crop systems and its potential to sequester carbon in soils. Soil & Tillage Research, 246, 106330. https://doi.org/10.1016/j.still.2024.106330

18. IPCC. (2023). Summary for policymakers. In H. Lee & J. Romero (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1–34). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647.001

19. Jarvis, A., & Forster, P. M. (2024). Estimated human-induced warming from a linear temperature and atmospheric CO2 relationship. Nature Geoscience, 17(12), 1222–1224. https://doi.org/10.1038/s41561-024-01580-5

20. Jiang, B., Li, J., Yang, Y., Zhang, J., Tian, X., Zhang, X., & Meng, Q. (2025). Wetland CH4 and CO2 emissions show opposite temperature dependencies along global climate gradients. Catena, 248, 108557. https://doi.org/10.1016/j.catena.2024.108557

21. Kim, J. H., Jobbágy, E. G., Richter, D. D., Trumbore, S. E., & Jackson, R. B. (2020). Agricultural acceleration of soil carbonate weathering. Global Change Biology, 26(10), 5988–6002. https://doi.org/10.1111/gcb.15207

22. Kong, F., Xu, Y., Du, H., He, Y., & Zheng, C. (2025). Spatio-temporal evolution of water erosion in the western Songnen Plain: Analysis of its response to land use dynamics and climate change. Soil & Tillage Research, 245, 106299. https://doi.org/10.1016/j.still.2024.106299

23. Lal, R. (2023). Carbon farming by recarbonization of agroecosystems. Pedosphere, 33(5), 676–679. https://doi.org/10.1016/j.pedsph.2023.07.024

24. Li, J., Liu, F., Shi, W., Du, Z., Deng, X., Ma, Y., Shi, X., Zhang, M., & Li, Q. (2024). Including soil depth as a predictor variable increases prediction accuracy of SOC stocks. Soil & Tillage Research, 238, 106007. https://doi.org/10.1016/j.still.2024.106007

25. Li, R., Hu, W. Y., Jia, Z. J., Liu, H. Q., Zhang, C., Huang, B., Yang, S. H., Zhao, Y. G., Zhao, Y. C., Shukla, M. K., & Taboada, M. A. (2025). Soil degradation: A global threat to sustainable use of black soils. Pedosphere, 35(1), 264–279. https://doi.org/10.1016/j.pedsph.2024.06.011

26. Lin, Z. Q., Dai, Y. J., Mishra, U., Wang, G. C., Shangguan, W., Zhang, W., & Qin, Z. C. (2024). Global and regional soil organic carbon estimates: Magnitudes and uncertainties. Pedosphere, 34(4), 685–698. https://doi.org/10.1016/j.pedsph.2023.06.005

27. Ma, Y., & Jiang, Z. (2025). Effects of long-term modified conservation tillage on carbon sequestration, microbial communities, and crop productivity in northeastern Chinese Mollisols. Pedosphere. https://doi.org/10.1016/j.pedsph.2025.03.009

28. MapBiomas. (2024a). Projeto MapBiomas – Coleção 9 da Série Anual de Mapas de Cobertura e Uso da Terra do Brasil. https://doi.org/10.58053/MapBiomas/XXUKA8

29. MapBiomas. (2024b). Coleção 2 (beta) da série de mapas anuais do estoque de carbono orgânico do solo do Brasil (1985-2023). https://doi.org/10.58053/MapBiomas/TVRX77

30. MapBiomas. (2025). RAD2024: Relatório Anual do Desmatamento no Brasil 2024. MapBiomas. https://alerta.mapbiomas.org/wp-content/uploads/sites/17/2025/05/RAD2024_15.05.pdf

31. Moreira, F. M. S., & Siqueira, J. O. (2006). Microbiologia e bioquímica do solo (2nd ed.). UFLA.

32. Nayak, A. K., Tripathi, R., Debnath, M., Swain, C. K., Dhal, B., Vijaykumar, S., Nayak, A. D., Mohanty, S., Shahid, M., Kumar, A., Rajak, M., Moharana, K. C., Chatterjee, D., Munda, S., Guru, P., Khanam, R., Lal, B., Gautam, P., Pattanaik, S., Shukla, A. K., Fitton, N., Smith, P., & Pathak, H. (2023). Carbon and water footprints of major crop production in India. Pedosphere, 33(3), 448–462. https://doi.org/10.1016/j.pedsph.2022.06.045

33. Nazir, M. J., Li, G., Nazir, M. M., Zulfiqar, F., Siddique, K. H. M., Iqbal, B., & Du, D. (2024). Harnessing soil carbon sequestration to address climate change challenges in agriculture. Soil & Tillage Research, 237, 105959. https://doi.org/10.1016/j.still.2023.105959

34. Observatório do Clima. (2024). Nota técnica - Bases para proposta de 2ª NDC para o Brasil. https://oc.eco.br/nota-tecnica-bases-para-proposta-de-2a-ndc-para-o-brasil/

35. Oliveira, D. M. S., Tavares, R. L. M., Loss, A., Madari, B. E., Cerri, C. E. P., Alves, B. J. R., Pereira, M. G., & Cherubin, M. R. (2023). Climate-smart agriculture and soil C sequestration in Brazilian Cerrado: A systematic review. Revista Brasileira de Ciência do Solo, 47, e0220055. https://doi.org/10.36783/18069657rbcs20220055

36. Padarian, J., Minasny, B., McBratney, A. B., & Smith, P. (2021). Additional soil organic carbon storage potential in global croplands. SOIL Discuss. [Preprint]. https://doi.org/10.5194/soil-2021-73

37. Pan, J., Yang, Y., Zhang, J., Tian, X., Zhang, X., & Meng, Q. (2025). Agroforestry increases soil carbon sequestration, especially in arid areas: A global meta-analysis. Catena, 249, 108667. https://doi.org/10.1016/j.catena.2024.108667

38. Paramesha, V., Kumar, A., Vishnuvardhan, R. K. M., Sreedevi, B., Rani, B., Sahoo, S., & Jat, R. A. (2025). Evaluating land use and climate change effects on soil organic carbon: A simulation study in coconut and pineapple systems in west coast India. Catena, 248, 108587. https://doi.org/10.1016/j.catena.2024.108587

39. Petersson, T., Antoniella, G., Perugini, L., Chiriacò, M. V., & Chiti, T. (2025). Carbon farming practices for European cropland: A review on the effect on soil organic carbon. Soil & Tillage Research, 247, 106353. https://doi.org/10.1016/j.still.2024.106353

40. Qiu, J. C., Song, M. H., Wang, C. M., Dou, X. M., Liu, F. F., Wang, J. X., Zhu, C. Y., & Wang, S. Q. (2023). Five-year warming does not change soil organic carbon stock but alters its chemical composition in an alpine peatland. Pedosphere, 33(5), 776–787. https://doi.org/10.1016/j.pedsph.2023.03.021

41. Raza, S., Ali, B., Be, M. A., Zamanian, K., Karimzadeh, J., Li, H., Liesack, W., & Kuzyakov, Y. (2021). Inorganic carbon losses by soil acidification jeopardize global efforts on carbon sequestration and climate change mitigation. Journal of Cleaner Production, 319, 128036. https://doi.org/10.1016/j.jclepro.2021.128036

42. Ren, T., Zhang, J., Yang, Y., Tian, X., Zhang, X., & Meng, Q. (2025). Asymmetric responses of soil dissolved organic carbon and dissolved organic nitrogen to warming: A meta-analysis. Catena, 252, 108871. https://doi.org/10.1016/j.catena.2025.108871

43. Rezende, E. I. P., Angelo, L. C., Santos, S. S. dos, & Mangrich, A. S. (2011). Biocarvão (biochar) e sequestro de carbono. Revista Virtual de Química, 3(5), 426–433. https://doi.org/10.5935/1984-6835.20110046

44. Ribeiro, J. M., Freitas, I. C., Brito, B. G. S., Fernandes, L. A., Leite, L. F. C., Barbosa, D. L. A., Santos, M. V., Cerri, C. E. P., & Frazão, L. A. (2023). Agrosilvopastoral system as a potential model for increasing soil carbon stocks: A century model approach. Revista Brasileira de Ciência do Solo, 47, e0220136. https://doi.org/10.36783/18069657rbcs20220136

45. Riebeek, H. (n.d.). O ciclo do carbono. Earth Observatory – NASA. https://earthobservatory.nasa.gov/features/CarbonCycle/page1.php

46. Shao, P. S., Han, H. Y., Sun, J. K., & Xie, H. T. (2023). Effects of global change and human disturbance on soil carbon cycling in boreal forest: A review. Pedosphere, 33(1), 194–211. https://doi.org/10.1016/j.pedsph.2022.06.035

47. Sharififar, A., Minasny, B., McBratney, A. B., & Sparks, D. L. (2023). Soil inorganic carbon, the other and equally important soil carbon pool: Distribution, controlling factors, and the impact of climate change. In D. L. Sparks (Ed.), Advances in Agronomy (Vol. 178, pp. 165–231). Academic Press. https://doi.org/10.1016/bs.agron.2022.11.005

48. Shen, R. F., & Teng, Y. (2023). The frontier of soil science: Soil health. Pedosphere, 33(1), 6–7. https://doi.org/10.1016/j.pedsph.2022.06.007

49. Siddique, K. H. M., Bolan, N., Rehman, A., & Farooq, M. (2024). Enhancing crop productivity for recarbonizing soil. Soil & Tillage Research, 235, 105863. https://doi.org/10.1016/j.still.2023.105863

50. Song, X., Corti, G., Shen, R. F., & Zhang, J. B. (2025). Soil health for future generations: Ensuring sustainable agriculture and ecosystem resilience. Pedosphere, 35(1), 1–2. https://doi.org/10.1016/j.pedsph.2025.01.007

51. Souza, I. F., Gomes, L. C., Fernandes Filho, E. I., & Silva, I. R. (2021). Hierarchical feedbacks of vegetation and soil carbon pools to climate constraints in Brazilian ecosystems. Revista Brasileira de Ciência do Solo, 45, e0210079. https://doi.org/10.36783/18069657rbcs20210079

52. Taboada, M. Á., Costantini, A. O., Busto, M., Bonatti, M., & Sieber, S. (2021). Climate change adaptation and the agricultural sector in South American countries: Risk, vulnerabilities and opportunities. Revista Brasileira de Ciência do Solo, 45, e0210072. https://doi.org/10.36783/18069657rbcs20210072

53. Tonucci, R. G., Vogado, R. F., Silva, R. D., Pompeu, R. C. F. F., Oda-Souza, M., & Souza, H. A. (2023). Agroforestry system improves soil carbon and nitrogen stocks in depth after land-use changes in the Brazilian semi-arid region. Revista Brasileira de Ciência do Solo, 47, e0220124. https://doi.org/10.36783/18069657rbcs20220124

54. Usman, S. (2025). Advanced soil conservation for African drylands: From erosion models to management theories. Pedosphere. https://doi.org/10.1016/j.pedsph.2025.01.012

55. Wang, L., Wang, E., Chen, G., Qian, X., Liu, Q., Gao, Y., Zhang, H., Liu, K., & Li, Z. (2025). Optimizing straw return to enhance grain production and approach carbon neutrality in the intensive cropping systems. Soil & Tillage Research, 248, 106447. https://doi.org/10.1016/j.still.2025.106447

56. Wang, M. Y., Shi, X. Z., Yu, D. S., Xu, S. X., Tan, M. Z., Sun, W. X., & Zhao, Y. C. (2013). Regional differences in the effect of climate and soil texture on soil organic carbon. Pedosphere, 23(6), 799–807. https://doi.org/10.1016/S1002-0160(13)60071-7

57. Wang, S., Sun, N., Zhang, X., Hu, C., Wang, Y., Xiong, W., Zhang, S., Colinet, G., Xu, M., & Wu, L. (2024). Assessing the impacts of climate change on crop yields, soil organic carbon sequestration and $N_2O$ emissions in wheat-maize rotation systems. Soil & Tillage Research, 240, 106088. https://doi.org/10.1016/j.still.2024.106088

58. Xu, H., Wang, M., You, C., Tan, B., Xu, L., Li, H., Zhang, L., Wang, L., Liu, S., Hou, G., Liu, Y., Xu, Z., Sardans, J., & Penuelas, J. (2024). Warming effects on C:N:P stoichiometry and nutrient limitation in terrestrial ecosystems. Soil & Tillage Research, 235, 105896. https://doi.org/10.1016/j.still.2023.105896

59. Yeasmin, S., Singh, B., Johnston, C. T., Hua, Q., & Sparks, D. L. (2023). Changes in particulate and mineral-associated organic carbon with land use in contrasting soils. Pedosphere, 33(3), 421–435. https://doi.org/10.1016/j.pedsph.2022.06.042

60. Zamanian, K., Zhou, J., & Kuzyakov, Y. (2021). Soil carbonates: The unaccounted, irrecoverable carbon source. Geoderma, 384, 114817. https://doi.org/10.1016/j.geoderma.2020.114817

61. Zhao, Y., Wang, X., Jiang, S., Wu, J., Yuan, M., Li, Y., Li, J., Duan, W., & Wang, J. (2025). Successive utilization of carbon from different biogenic sources leads to continuous enhancement of soil respiration. Soil & Tillage Research, 246, 106327. https://doi.org/10.1016/j.still.2024.106327

62. Zheng, J., Zhang, X., Li, X., Yang, P., Zhao, J., Wang, J., Xin, X., Yang, J., & Zhang, J. (2021). Interactive effects of mulching practice and nitrogen rate on grain yield, water productivity, fertilizer use efficiency and greenhouse gas emissions of rainfed summer maize in northwest China. Agricultural Water Management, 248, 106778. https://doi.org/10.1016/j.agwat.2021.106778

63. Zhuang, Q., Shao, Z., Kong, L., Huang, X., Li, Y., Yan, Y., & Wu, S. (2023). Assessing the effects of agricultural management practices and land-use changes on soil organic carbon stocks. Soil & Tillage Research, 231, 105716. https://doi.org/10.1016/j.still.2023.105716