

Soils and CO₂ emissions: perspectives on the emergence of the Anthropocene¹

Solos e emissões de CO₂: perspectivas sobre o surgimento do Antropoceno

Suelos y emisiones de CO₂: perspectivas sobre el surgimiento del Antropoceno

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ABSTRACT

This article analyses soil formation, carbon dioxide (CO₂) cycling, climate change, biodiversity loss, and the relationship of these dynamics to the emergence of the Anthropocene. The study aims to verify, through a literature review, the anthropogenic influences on climate change and to understand the relationship between soil formation and CO₂ cycling, considering the continuous exchange of this gas between the substrate and the atmosphere and its role in regulating the global climate. The contribution of activities such as agriculture and wildfires to the increase in CO₂ emissions and other gases associated with global warming is also discussed. The research was conducted based on the analysis of scientific articles indexed in academic databases, with an emphasis on publications between 2000 and 2024, using the descriptors “Climate Change,” “Carbon Dioxide,” “soil formation processes” and “Anthropocene.” The concept of the Anthropocene is approached as an interpretative framework for environmental transformations induced by human activities, evidenced by the increase in average global temperature, the intensification of extreme weather events, and the degradation of biodiversity. In the context of climate change, greenhouse gases (GHG) stand out, defined as atmospheric gases capable of absorbing and re-emitting infrared radiation, contributing to global warming. Mitigating these processes requires reducing GHG emissions, adopting adaptation measures, conserving vegetation cover, and implementing public policies geared towards environmental sustainability.

Keywords: Soil attributes. Gas emissions. Land use.

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RESUMO

Este artigo analisa a formação do solo, a ciclagem do dióxido de carbono (CO₂), as mudanças climáticas, a perda de biodiversidade e a relação dessas dinâmicas com o surgimento do Antropoceno. O estudo tem como objetivo verificar, por meio de revisão de literatura, as influências antrópicas nas mudanças climáticas e compreender a relação entre a formação do solo e a ciclagem do CO₂, considerando a troca contínua desse gás entre o substrato e a atmosfera e seu papel na regulação do clima global. Discute-se, ainda, a contribuição de atividades como a agricultura e as queimadas para o aumento das emissões de CO₂ e de outros gases associados ao aquecimento global. A pesquisa foi conduzida com base na análise de artigos científicos indexados em bases acadêmicas, com ênfase em publicações entre 2000 e 2024, a partir dos descritores “Mudanças Climáticas”, “Dióxido de Carbono”, “processos de formação dos solos” e “Antropoceno”. O conceito de Antropoceno é abordado como marco interpretativo das transformações ambientais induzidas pelas atividades humanas, evidenciadas pelo aumento da temperatura média global, pela intensificação de eventos climáticos extremos e pela degradação da biodiversidade. No contexto das mudanças climáticas, destacam-se os gases de efeito estufa (GEE), conhecidos internacionalmente como greenhouse gases (GHG), definidos como gases atmosféricos capazes de absorver e reemitir radiação infravermelha, contribuindo para o aquecimento do planeta. A mitigação desses processos requer a redução das emissões de GEE, a adoção de medidas de adaptação, a conservação da cobertura vegetal e a implementação de políticas públicas orientadas à sustentabilidade ambiental.

Palavras-Chaves: Atributos do solo. Emissão de gases. Uso da terra.

RESUMEN

Este artículo analiza la formación del suelo, el ciclo del dióxido de carbono (CO₂), el cambio climático, la pérdida de biodiversidad y la relación de estas dinámicas con el surgimiento del Antropoceno. El estudio tiene como objetivo verificar, mediante una revisión de la literatura, las influencias antrópicas sobre el cambio climático y comprender la relación entre la formación del suelo y el ciclo del CO₂, considerando el intercambio continuo de este gas entre el sustrato y la atmósfera y su papel en la regulación del clima global. Asimismo, se analiza la contribución de actividades como la agricultura y las quemaduras al aumento de las emisiones de CO₂ y de otros gases asociados al calentamiento global. La investigación se llevó a cabo a partir del análisis de artículos científicos indexados en bases de datos académicas, con énfasis en publicaciones entre 2000 y 2024, utilizando los descriptores “Cambio Climático”, “Dióxido de Carbono”, “procesos de formación de los suelos” y “Antropoceno”. El concepto de Antropoceno se aborda como un marco interpretativo de las transformaciones ambientales inducidas por las actividades humanas, evidenciadas por el aumento de la temperatura media global, la intensificación de los fenómenos climáticos extremos y la degradación de la biodiversidad. En el contexto del cambio climático, destacan los gases de efecto invernadero (GEI), conocidos internacionalmente como greenhouse gases (GHG), definidos como gases atmosféricos capaces de absorber y reemitir radiación infrarroja, contribuyendo al calentamiento del planeta. La mitigación de estos procesos requiere la reducción de las emisiones de GEI, la adopción de medidas de adaptación, la conservación de la cobertura vegetal y la implementación de políticas públicas orientadas a la sostenibilidad ambiental.

Palabras clave: Atributos del suelo. Emisión de gases. Uso de la tierra.

INTRODUCTION

Soils are present across much of the Earth's landscapes and constitute a fundamental natural resource in the surface portion of the Earth (Coelho *et al.*, 2013). Their formation results from the dynamic interaction of factors such as parent material, climate, relief, organisms, and time, whose combined action promotes pedogenetic processes that manifest with different intensities across the landscape (Pereira *et al.*, 2019).

In the scientific literature, definitions of soil vary according to its properties and uses; in this work, soil is understood as a collection of dynamics containing living matter, resulting from the action of climate and the biosphere on rock, whose transformation occurs over time under the influence of relief (Silva, 2011, p. 93). From this perspective, soil actively participates in essential environmental processes, among which the biogeochemical cycles of water, phosphorus, nitrogen, and, especially, carbon stand out (Silva *et al.*, 2021).

Soil formation, called pedogenesis, involves processes of decomposition, transport, and deposition of materials derived from the parent rock, driven by transforming agents such as weathering (Antunes *et al.*, 2015). However, anthropic interventions have significantly modified these natural processes, altering the dynamics of soil formation and functioning. Among the main human actions affecting the Earth system are deforestation, burning, and agricultural expansion, practices that contribute to the release of carbon dioxide (CO₂) into the atmosphere and to the intensification of global climate change (Oliveira *et al.*, 2025). The removal of vegetation cover, in addition to fragmenting natural habitats, reduces carbon sequestration capacity and can turn exposed soil into a potentially carbon-emitting system, making it an active component in contemporary climate dynamics (Barbosa, 2017).

Given this context, it becomes essential to understand the relationships between pedogenetic processes, carbon cycling, and the environmental transformations associated with human activities. In this sense, this article aims to analyze, through a literature review, the relationship between soil formation, CO₂ dynamics, biodiversity loss, and climate change, interpreting these interactions in light of the scientific debate on the Anthropocene. It is assumed that the transformations in the carbon cycle mediated by soil and intensified by anthropic land use constitute evidence of the reorganization of the Earth System, a central feature of contemporary discussions on the emergence of a new geological epoch marked by human influence.

METHODOLOGY

This study is characterized as a systematized bibliographic review, of an exploratory nature and qualitative approach, conducted with the aim of ensuring greater methodological rigor, transparency, and reproducibility in the process of selecting and analysing the scientific literature. According to Silva *et al.* (2021), bibliographic research with a qualitative focus seeks to problematize, question, and articulate prior knowledge

with new knowledge, promoting the development of specific and reflective ideas. In this sense, a structured search strategy was adopted, with prior definition of descriptors, explicit inclusion and exclusion criteria, and clear stages of screening, eligibility, and analysis of the selected studies.

Searches were conducted between March and June 2024 in the Google Scholar and Portal de Periódicos da Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) databases. The choice of these databases is justified by their broad multidisciplinary coverage, relevance to environmental sciences, and access to peer-reviewed national and international scientific production, allowing greater breadth and robustness in identifying studies pertinent to the topic. Descriptors in Portuguese and English were used, combined by Boolean operators, with the aim of broadening the scope of the search, reducing linguistic biases, and incorporating contributions from the international scientific debate. The strategy adopted was: (“Mudanças Climáticas” OR “Climate Change”) AND (“Dióxido de Carbono” OR “Carbon Dioxide”) AND (“Processos de formação dos solos” OR “Soil formation processes”) AND (“Antropoceno” OR “Anthropocene”). The search was applied to the title, abstract, and keyword fields. In the CAPES Periodicals Portal, an additional refinement was carried out by knowledge areas, including Biological Sciences, Exact and Earth Sciences, Agricultural Sciences, and Multidisciplinary areas. The time frame covered the period from 2000 to 2024, considering the consolidation of the contemporary scientific debate on climate change and the Anthropocene throughout the 21st century.

The initial application of the descriptors resulted in 38,680 records in Google Scholar and 1,126 records in the CAPES Portal. After reading the titles and abstracts to verify thematic adherence to the research objective, 17,531 records in Google Scholar and 360 in the CAPES Portal were considered potentially relevant. These studies were then submitted to a more rigorous screening stage, based on the previously established inclusion and exclusion criteria. Scientific articles published in peer-reviewed journals, between 2000 and 2024, written in Portuguese and English, that addressed in an integrated manner at least two of the following thematic axes were included: the carbon cycle with emphasis on CO₂ fluxes, pedogenetic processes and soil dynamics, climate change, and conceptual or scientific discussion on the Anthropocene. Opinion articles, journalistic texts, essays without explicit methodology, narrative reviews without defined criteria, book chapters, conference proceedings, patents, and technical documents without peer review were

excluded, as were studies that mentioned the descriptors peripherally, without an effective connection between soil, carbon, and climate change.

The potentially relevant studies were submitted to full reading to verify compliance with the established criteria. At the end of the eligibility process, 32 articles fully met the methodological requirements and constituted the final corpus of the analysis, 17 from Google Scholar and 15 from the CAPES Portal. These figures correspond to 0.044% of the records initially identified in Google Scholar and 1.70% in the CAPES Portal, evidencing the rigor of the selection criteria adopted.

The analysis of the selected studies was conducted through analytical and comparative reading, with identification of theoretical convergences, recurring conceptual categories, and relationships between pedogenetic processes, carbon dynamics, and climate change. The results were organized in an interpretive manner into interrelated thematic axes, allowing the integration of biophysical foundations and conceptual discussions on the role of soil in carbon fluxes and in the contemporary transformations of the climate system. This approach enabled the construction of a theoretical synthesis coherent with the objectives of the study, indicating soil as a central component in understanding the environmental changes associated with the Anthropocene.

Table 1. Number of records retrieved from the CAPES Periodicals Portal and Google Scholar databases between 2000 a 2024, based on the Keywords used in the search.

Keywords	Journals of the Coordination for the Improvement of Higher Education Personnel (CAPES)	Google Scholar
“Mudanças Climáticas” OR “Climate Change”	208	20.600
“Dióxido de Carbono” OR “Carbon Dioxide”	661	2.980
“Antropoceno” OR “Anthropocene”	4	15.100
“Processo de formação dos Solos” OR “Soil formation processes”	253	37
TOTAL	1.126	38.717

Source: Prepared by the authors (2026).

The distribution of records retrieved in the searches conducted between 2000 and 2024 in the CAPES Periodicals Portal and Google Scholar databases, based on the descriptors defined in the search strategy, is presented in Table 1. It is observed that the keyword “Climate Change” concentrated the highest number of occurrences, evidencing the breadth and consolidation of this field in contemporary scientific production.

Despite the high initial volume of records, the application of the inclusion and exclusion criteria allowed the set of studies to be refined to 32 articles, ensuring thematic adherence and methodological consistency of the analysed corpus. The distribution of results also reveals differences in coverage between the databases, as in the case of the descriptor “Soil formation process,” which presented a lower number of records in Google Scholar compared to the CAPES Portal, and the term “Anthropocene,” whose presence proved to be considerably lower in the CAPES Portal compared to Google Scholar. These results reinforce the importance of rigorous screening procedures to ensure the relevance and scientific quality of the included studies, contributing to a more robust analysis of the relationships between carbon, climate change, and the Anthropocene.

DEVELOPMENT

Carbon and climate change

Carbon is a fundamental element for the functioning of the Earth’s climate system, participating in biophysical processes essential to the maintenance of life and the planet’s energy balance (Friedlingstein *et al.*, 2023). In the atmosphere, its main form is carbon dioxide (CO₂), a greenhouse gas capable of absorbing and re-emitting infrared radiation, contributing to the thermal regulation of the Earth (Junges *et al.*, 2018). Although the greenhouse effect is a natural phenomenon essential to the planet’s habitability, the anthropic increase in atmospheric CO₂ concentrations has intensified global warming and generated significant changes in the climate system (Schimel *et al.*, 2016).

As discussed by Junges *et al.* (2018), the greenhouse effect maintains the planet’s average temperature at levels compatible with life by retaining part of the energy from the Sun. However, the increase in greenhouse gas concentrations resulting from human activities has altered the atmosphere’s energy balance, promoting greater heat retention and contributing to the rise in global average temperature (Ayoub *et al.*, 2024). Among the gases associated with this process, carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) stand out, whose intensification is directly related to changes in land use, the burning of fossil fuels, and contemporary productive activities (Hansen *et al.*, 2007).

In this sense, the persistent rise in atmospheric CO₂ concentrations has come to be understood, in the contemporary scientific debate, as evidence of the growing human influence on the Earth System (Santos, 2018). Thus, climate change associated with human

action constitutes not only an environmental phenomenon, but a systemic expression of the reorganization of the relationships between society and nature.

Redin *et al.* (2011) highlight that practices such as deforestation and agricultural expansion, intensified throughout history, especially after the Industrial Revolution, contributed to the alteration of global biogeochemical cycles. Evidence of these transformations can be observed in paleoclimatic records, such as ice cores, which allow the reconstruction of historical variations in atmospheric composition and global temperatures (Silva *et al.*, 2018a; Pereira, 2019). These records preserve information on concentrations of gases, particles, and pollutants over time, evidencing the recent increase in human interference in natural systems.

The global warming resulting from these transformations has produced broad environmental impacts, including changes in precipitation regimes, glacier melting, sea level rise, biodiversity loss, and the intensification of extreme weather events (Nunes *et al.*, 2017). In this context, understanding climate change requires an integrated analysis of the global carbon reservoirs, among which soil occupies a strategic position in regulating atmospheric CO₂ concentrations. Thus, changes in atmospheric carbon concentrations do not represent merely isolated environmental variations but constitute evidence of the growing anthropic influence on the global climate system, configuring one of the main markers of the transformations associated with the Anthropocene.

Pedogenic process and carbon cycle

According to Smith *et al.* (2020), soil represents an essential component of the Earth system, acting as an important carbon reservoir and playing a central role in climate regulation. Soil formation results from the joint action of physical, chemical, and biological processes on the parent material, under the influence of climate, relief, time, and organisms (Pereira *et al.*, 2019).

Over geological time, rocks are weathered by physical and chemical processes that promote their fragmentation and mineralogical transformation. The action of water, oxygen, and carbon dioxide contributes to the decomposition and reorganization of materials, giving rise to soil as a dynamic system (Toledo *et al.*, 2014). This set of transformations, called pedogenesis, results in the formation of soil horizons that constitute an environment favourable to the development of vegetation cover (Lepsch, 2010). In this context, vegetation plays a fundamental role in the carbon cycle by removing CO₂ from the

atmosphere through photosynthesis and transferring it to the soil in the form of organic matter (Friedlingstein *et al.*, 2023). Part of this carbon is stabilized in the soil system, while another portion returns to the atmosphere through biological respiration, forming a continuous flow between the biosphere and the atmosphere (Buckeridge; Aidar, 2002). In this way, soil acts simultaneously as a reservoir and a potential source of carbon, depending on environmental conditions and forms of land use.

The presence of carbon in the soil is directly related to the biological processes that sustain life, including photosynthesis and nutrient cycling (Machado, 2005; Lopes, 2017). Thus, the balance of the carbon cycle depends on the maintenance of the integrity of natural systems, being strongly influenced by human interventions on vegetation cover and land use. From a contemporary analytical perspective, soil can be understood as a material record of the environmental transformations induced by human action, evidencing changes in carbon flows, ecosystem structure, and the functioning of terrestrial systems (Alves *et al.*, 2024).

Anthropogenic transformations and alterations to natural systems

Human influence on the environment intensified significantly following the Industrial Revolution, a period marked by the expansion of fossil fuel use, population growth, and the growth of productive activities (Machado, 2005). These transformations caused profound changes in the terrestrial landscape, particularly through deforestation and agricultural expansion, processes that reduced the capacity of ecosystems to store carbon (Foley *et al.*, 2005).

The conversion of natural areas into productive systems modifies the physical, chemical, and biological properties of soils, reducing soil organic matter stocks and compromising essential ecological functions (Capeche, 2012). Furthermore, the intensification of agricultural activities, associated with the use of fertilizers and pesticides, may generate additional environmental impacts, affecting terrestrial and aquatic systems and interfering with biogeochemical cycles (Spadotto; Spadotto, 2006; Nunes *et al.*, 2017).

Deforestation and wildfires stand out among the main factors responsible for releasing large amounts of CO₂ into the atmosphere (Buckeridge *et al.*, 2007; Barbosa, 2017). These transformations reduce the carbon sequestration potential of ecosystems and contribute to increasing atmospheric concentrations of greenhouse gases (Alves *et al.*,

2024). In this context, land use and land cover changes constitute one of the main contemporary drivers of global climate system change.

Population growth and the expansion of human activities have intensified these environmental pressures, promoting transformations on a planetary scale and highlighting the interdependence between social and natural processes (Mello *et al.*, 2017). Thus, changes in land use and land cover, by altering soil carbon stocks and carbon fluxes between the biosphere and the atmosphere, demonstrate that the soil system acts as a mediator between human activities and global climate change.

According to Varney *et al.* (2024), soil not only responds to anthropogenic pressures but also constitutes a central component in the materialization of contemporary environmental transformations. In this sense, soils represent the largest terrestrial carbon reservoir and play a decisive role in regulating carbon exchanges between the Earth's surface and the atmosphere under land use change, providing an empirical basis for interpreting changes in the functioning of the Earth System associated with the Anthropocene (Rockström *et al.*, 2009). These transformations, by reaching a planetary scale and leaving measurable records in natural systems, support the scientific interpretation that human activity has become a relevant geological force.

Anthropocene and reorganization of the Earth System

The discussions presented in the previous sections, particularly those related to changes in the carbon cycle and land use transformations, provide an empirical basis for understanding the Anthropocene. Changes in carbon stocks, ecosystem dynamics, and the functioning of terrestrial systems demonstrate that human activity has become a force capable of modifying natural processes on a global scale (Corrêa, 2025). In this context, the Anthropocene can be understood as the period in which human influence on the Earth's biophysical systems became significant enough to alter their functioning and evolution.

Although there is no consensus regarding its formalization as a new geological epoch, the concept has gained prominence by extending beyond the field of geosciences and fostering debates about its causes, implications, and impacts on the planet (Ferrão, 2018). Thus, rather than simply representing a chronological proposal, the Anthropocene constitutes a scientific interpretation that seeks to understand the magnitude of anthropogenic changes in natural systems, such as climate change, biodiversity loss, and

alterations in biogeochemical cycles, based on the material evidence of these transformations (Zalasiewicz, 2017; Zalasiewicz *et al.*, 2023).

Among this evidence are changes in carbon fluxes, alterations in atmospheric composition resulting from the emission of gases and aerosols, modifications in soil carbon stocks, and changes in land use and land cover, all of which reveal measurable anthropogenic interference in biogeochemical cycles and in the functioning of the climate system (Artaxo, 2014; Luz; Marçal, 2016). Therefore, the proposition of the Anthropocene implies recognizing that the transformations observed in natural systems do not constitute isolated phenomena but rather express structural changes in the functioning of the Earth System mediated by contemporary socio-environmental processes (Steffen *et al.*, 2011).

The scientific debate on the Anthropocene involves different interpretations regarding its onset and its environmental markers. Some approaches relate its origin to the development of agriculture and the increase in atmospheric CO₂ concentrations (Albuquerque; Souza, 2022), while others associate its emergence with the transgression of planetary boundaries related to environmental stability (Viola; Basso, 2016; Silva; Arbilla, 2018b). These boundaries include changes in climate, biogeochemical cycles, biodiversity, and land use, reflecting the magnitude of the transformations induced by human activities (Marques, 2022).

From this perspective, soil assumes a central role in understanding the Anthropocene, as it materially records environmental transformations and actively participates in climate dynamics through carbon storage and release. According to Roubuste *et al.* (2022), changes in soil carbon stocks, shifts in vegetation cover, and ecosystem degradation demonstrate the reconfiguration of the functioning of the Earth System. Furthermore, the IPCC report (2022) indicates that the intensification of climate change and biodiversity loss on a global scale is associated with factors such as greenhouse gas emissions, land use change, and environmental pollution. The World Wildlife Fund (2022; 2024) reports consistent trends of increasing global mean temperature, intensification of extreme events, and growth in the number of threatened species, reinforcing the understanding that contemporary transformations reflect systemic changes in the relationships between society and nature.

Complementarily, the assessment reports of the Intergovernmental Panel on Climate Change (IPCC) document the recent occurrence of climate change, as well as the ongoing degradation of biodiversity and of nature's contributions to human society. These

trends are associated with factors such as greenhouse gas emissions resulting from the burning of fossil fuels, habitat conversion and degradation, pollution, unsustainable practices, and the introduction of invasive species (Melo, 2023). Thus, the integrated analysis of climate change, carbon dynamics, and soil transformations demonstrates that these processes do not constitute isolated phenomena but rather express a structural change in the functioning of the planet, which is a central characteristic of discussions on the Anthropocene (Steffen *et al.*, 2015).

In this context, climate change mitigation strategies, such as reducing greenhouse gas emissions and increasing carbon sequestration in terrestrial ecosystems, play a fundamental role (Heath *et al.*, 2005). Practices such as reforestation and sustainable soil management contribute to carbon fixation in biomass and soil, reinforcing the importance of ecosystems as natural carbon sinks and their relevance in addressing climate change (Silva, 2018c). Furthermore, initiatives aimed at sustainable development, such as those established under the 2030 Agenda, emphasize the need to integrate climate change mitigation and adaptation, considering their impacts on food security, water security, and public health.

FINAL CONSIDERATIONS

The analysis conducted demonstrates that the interactions among climate change, carbon dynamics, and pedogenetic processes constitute central elements for understanding contemporary environmental transformations. The studies reviewed indicate that soil plays a strategic role both as a carbon reservoir and as a carbon source, directly influencing the balance of CO₂ fluxes and, consequently, the functioning of the climate system.

The evidence indicates that changes in land use and land cover, associated with the intensification of human activities, have promoted significant modifications in soil carbon stocks, contributing to increased greenhouse gas emissions. In this context, sustainable management and soil conservation practices emerge as fundamental strategies for mitigating environmental impacts and enhancing carbon sequestration. These processes reinforce that soil acts as a key element in mediating the relationship between anthropogenic activities and global climate change.

From this perspective, soil also constitutes a material record of contemporary environmental transformations, providing an empirical basis for interpreting changes in the functioning of the Earth System associated with the Anthropocene. The integration of

ecological, geographical, and climatic approaches proved essential for understanding the complexity of the processes analysed, allowing for a broader interpretation of the relationships among soil, atmosphere, and biosphere, and highlighting the need for interdisciplinary studies that consider multiple spatial and temporal scales.

Finally, it is noteworthy that understanding these dynamics contributes to advancing the scientific debate on the Anthropocene by highlighting the role of soil as a central component in the reorganization of the Earth System. These findings provide relevant support for the formulation of public policies and management strategies aimed at the sustainability of natural systems.

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