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REVIEW

Impact of land use change and climate on the Brazilian Amazon: a review on carbon stocks and greenhouse gas emissions

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Abstract

Historically, land-use changes in the Brazilian Amazon, such as the conversion of forests to pastures, have significantly impacted carbon and nitrogen cycles, contributing to greenhouse gas emissions and potentially compromising environmental sustainability. This review explores the effects of these changes on soil carbon and nitrogen stocks, emphasizing the role of sustainable practices and public policies in mitigating environmental impacts. Findings indicate that, although forest-to-pasture conversion may reduce soil organic carbon stocks by up to 11.3%, practices such as agroforestry systems, sustainable pasture management, and crop-livestock-forestry integration (CLFI) have the potential to reverse these effects by promoting carbon sequestration and soil conservation. Public policies such as the Low Carbon Agriculture Plan (ABC Plan) and the Amazon Fund are highlighted as essential pillars for sustainable development in the region. It is concluded that the adoption of sustainable agricultural practices, integrated with robust environmental policies and technological innovation, can transform the Amazon into a global model of balance between economic development and environmental conservation. Future studies should prioritize integrated assessments of carbon stocks, gas emissions, and socioeconomic indicators to support more effective and regionally adapted public policies.

Keywords: agriculture; environmental governance; livestock; soil carbon; sustainable practices; tropical soils climate.

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1. Introduction

Land use changes are among the main drivers of global climate change. They affect essential biogeochemical cycles, such as those of carbon and nitrogen, and intensify greenhouse gas (GHG) emissions (IPCC, 2019; Gasser et al., 2020). These changes have profound consequences for tropical ecosystems, particularly in the Brazilian Amazon, which plays a critical role as a global climate regulator and harbors one of the planet's greatest biodiversity (Gatti et al., 2021).

The process of aboveground biomass removal from tropical forests worldwide represents a net efflux of 425 Tg C year^{-1}, with 76.4% originating from tropical forests located in the Americas (Baccini et al., 2017). This conversion of forests into agricultural lands and pastures alters the ecological functionality of the region, resulting in significant GHG emissions and losses of soil carbon and nitrogen. By 2024, it is estimated that approximately 803,000 km^2 of the Amazon have been deforested, consolidating the so-called "Arc of Deforestation", a region already recognized for concentrating the greatest anthropogenic pressures, stretching from eastern Maranhão to Acre, through Pará, Mato Grosso, and Rondônia (SEEG, 2022; Domingues et al., 2020; INPE, 2025).

In addition to anthropogenic pressures, the unique climatic conditions of the Amazon, characterized by high humidity, elevated temperatures, intense precipitation regimes, and a predominance of soil organic carbon, increase the vulnerability of the region's soils (Sharififar et al., 2023). These conditions accelerate the decomposition of organic matter and promote nutrient leaching, amplifying the impacts of land-use change and aggravating environmental degradation (Albert et al., 2023).

Historically, logging has been among the main drivers of deforestation in the Amazon. In many cases, previously logged areas were converted to other land uses, such as cattle ranching, due to its lower initial cost and its role in securing land ownership. However, cattle ranching, when combined with sustainable management practices, has the potential to play an important role in environmental mitigation (Bogaerts et al., 2017; Silva et al., 2024).

Strategies such as rotational grazing, crop-livestock-forestry integration (CLFI), and the use of forage crop mixtures can minimize or even reverse soil organic carbon losses by promoting carbon sequestration and contributing to the recovery of degraded areas. These approaches allow livestock productivity to be aligned with environmental conservation, highlighting the importance of integrated strategies to mitigate climate impacts in the region (Azevedo et al., 2024; Abagandura et al., 2024; Souza et al., 2024).

Although there are several reviews on the impacts of climate change and land use in different regions and ecosystems of Brazil, studies that address the specific context of the Brazilian Amazon in an integrated and up-to-date manner are still rare. For instance, previous reviews have focused on national-scale climate projections, with emphasis on temperature and precipitation trends (Marengo et al., 2018), on the sustainability of agricultural production in the Amazon region (Bueno et al., 2021), and on the carbon sequestration potential of agricultural systems in the Cerrado biome (Oliveira et al., 2023).

Moreover, reviews such as those by Cotrufo & Lavallee (2022), Chien & Krumins (2023), and Sharififar et al. (2023) offer comprehensive syntheses on global mechanisms of organic and inorganic carbon storage in soils, as well as the effects of climate change on these processes. However, there is still a lack of recent reviews that articulate these perspectives with the current reality of the Brazilian Amazon, especially after 2020, a period marked by significant political, socioeconomic, and environmental transformations, such as the expansion of deforestation and the weakening of environmental policies.

In this context, this article aims to review the impacts of land-use changes and climatic conditions on soil carbon and nitrogen stocks, as well as on GHG emissions in the Brazilian Amazon. Additionally, it discusses sustainable management practices, such as agroforestry systems and the restoration of degraded areas, assessing their potential to mitigate environmental impacts and promote sustainable development. Finally, future directions for scientific research and the formulation of integrated public policies are presented, reinforcing the strategic role of the Amazon in addressing global climate change.

2. Land use changes and environmental impacts in the Brazilian Amazon

2.1 History of landscape transformations in the Amazon

The transformation of the Amazonian landscape began during the colonial period, particularly with the "drogas do sertão" cycle between the 17th and 18th centuries (Figure 1), when the region started supplying the European market with extractive products such as Brazil nuts, resins, oils, and spices (Gomes, 2018). During the same period, extractivism and the semi-domesticated cultivation of native cacao (*Theobroma cacao* L.) represented the first agricultural activity of significant economic relevance in the Amazon, lasting until the rise of cacao cultivation in southern Bahia (Schroth et al., 2016).

At the end of the 19th century, the rubber boom (*Hevea brasiliensis*) marked the peak of the extractive economy in the Amazon, positioning the region as the world's main supplier of natural latex until 1910, when the introduction of rubber trees in Southeast Asia led to the collapse of this cycle (Gomes, 2018). Although rubber extraction caused relatively limited impacts on forest cover, the subsequent agricultural expansion brought more lasting changes in land use, contributing to the transformation of the Amazon biome (Lapola et al., 2023).

In the 1960s and 1970s, structural public policies such as the National Integration Plan and the Amazon Development Plan intensified land-use changes. Aimed at integrating the Amazon region with the rest of the country, these initiatives promoted tax incentives, subsidized rural credit, and infrastructure projects, such as the construction of the Trans-Amazonian highway (Watrin et al., 2022). Although these policies boosted the economy, they overlooked environmental sustainability, resulting in uncontrolled deforestation, land conflicts, and negative impacts on traditional communities and small farmers (Arruda et al., 2023).

According to estimates from the Greenhouse Gas Emissions and Removals Estimation System (SEEG), over the past three decades, the land-use change, and forestry sector have been the main driver of deforestation. During this period, this sector accounted for 58% of national emissions, followed by agriculture, which contributed 21%. When analyzing Brazil's biomes, the land-use change, and forestry sector is responsible for 47% of emissions. Thus, both legal and illegal logging can be considered the primary drivers of deforestation.

Cattle ranching is frequently cited as one of the main drivers of deforestation in the Amazon (Danielson & Rodrigues, 2022; Lapola et al., 2023). Since the 1980s, it is estimated that approximately 68% of deforested areas have been converted into pastures, although not always immediately (Danielson & Rodrigues, 2022). Many of these areas were initially abandoned and only later converted to agricultural use, often by actors different from those responsible for the original deforestation (Lapola et al., 2023).

In addition to cattle ranching, practices such as slash-and-burn agriculture and low-technology farming systems have also contributed to deforestation, especially among smallholder farmers. These land-use practices, characterized by low productivity and intensive use of fire for land preparation, play a significant role in the early stages of land occupation. Shifting cultivation, often practiced with short fallow cycles, accelerates forest fragmentation and requires the constant clearing of new areas (Rodrigues et al., 2024).

In the 1990s, the growing global demand for soy and logging activities intensified forest fragmentation (Lapola et al., 2023). Consequently, forest cover loss became concentrated in the Legal Amazon, an area defined by the Brazilian government in 1953, encompassing all states in the North Region, as well as Mato Grosso and part of Maranhão. Despite its original purpose of promoting sustainable development, the unregulated expansion of agricultural frontiers and intensive logging consolidated the so-called "Arc of Deforestation" (Domingues et al., 2020; Assis et al., 2022).

This region exhibits high rates of deforestation and forest degradation, being responsible for significant carbon emissions (Figure 2). Data from PRODES indicate that, in 2024, cumulative deforestation in the Legal Amazon reached 6,268 km², representing a 22% reduction compared to the previous year (INPE, 2025). However, it is estimated that approximately 38% of the remaining forests in the region show some degree of degradation, with annual emissions ranging from 0.05 to 0.20 petagrams of carbon (Pg C), values comparable to or exceeding direct deforestation emissions (Lapola et al., 2023).

Habitat fragmentation, edge effects, forest fires, and extreme droughts increase the environmental vulnerability of this region. As a result, the "Arc of Deforestation" faces growing pressures that demand urgent mitigation actions. Key strategies include effective monitoring, the strengthening of public policies, and the implementation of sustainable practices that promote environmental recovery (Domingues et al., 2020; Pereira, 2022).

Despite the critical scenario, the "Arc of Deforestation" also represents a strategic opportunity to promote effective public policies that reconcile environmental conservation, social inclusion, and economic development. Integrated strategies such as continuous monitoring, incentives for sustainable land management, and reforestation can transform degraded areas into productive and environmental assets, with direct benefits for local communities (Santos et al., 2019; Badari et al., 2020; Gomes et al., 2024).

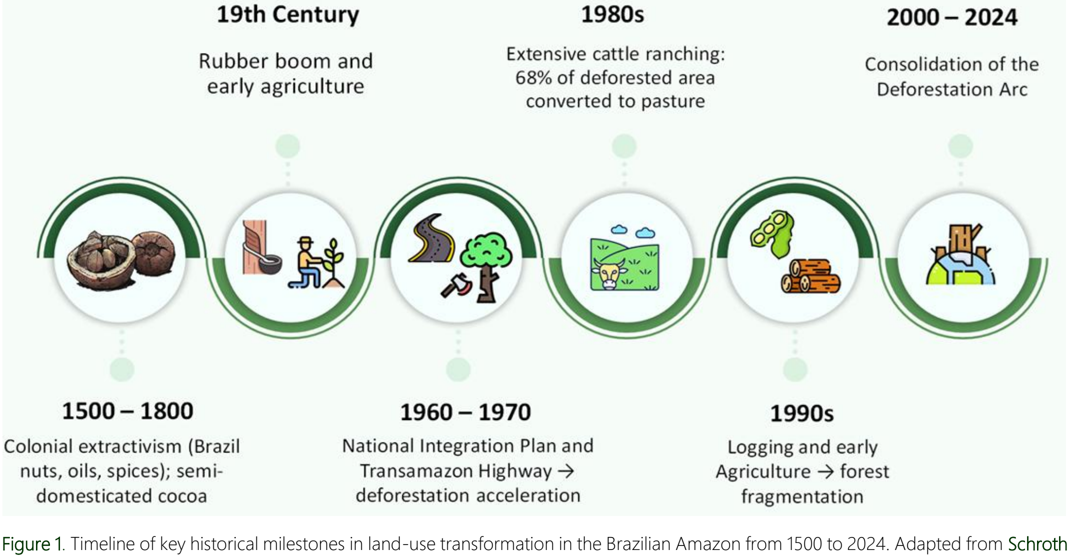

Figure 1. Timeline of key historical milestones in land-use transformation in the Brazilian Amazon from 1500 to 2024. Adapted from Schroth et al. (2016); Gomes et al. (2018); Chambouleyron & Ibáñez-Bonillo (2019); Gries et al. (2019); Amaral et al. (2019); Domingues et al. (2020); Winkler et al. (2021); Danielson & Rodrigues (2022); Watrin et al. (2022); Arruda et al. (2023); Albert et al. (2023); Lapola et al. (2023).

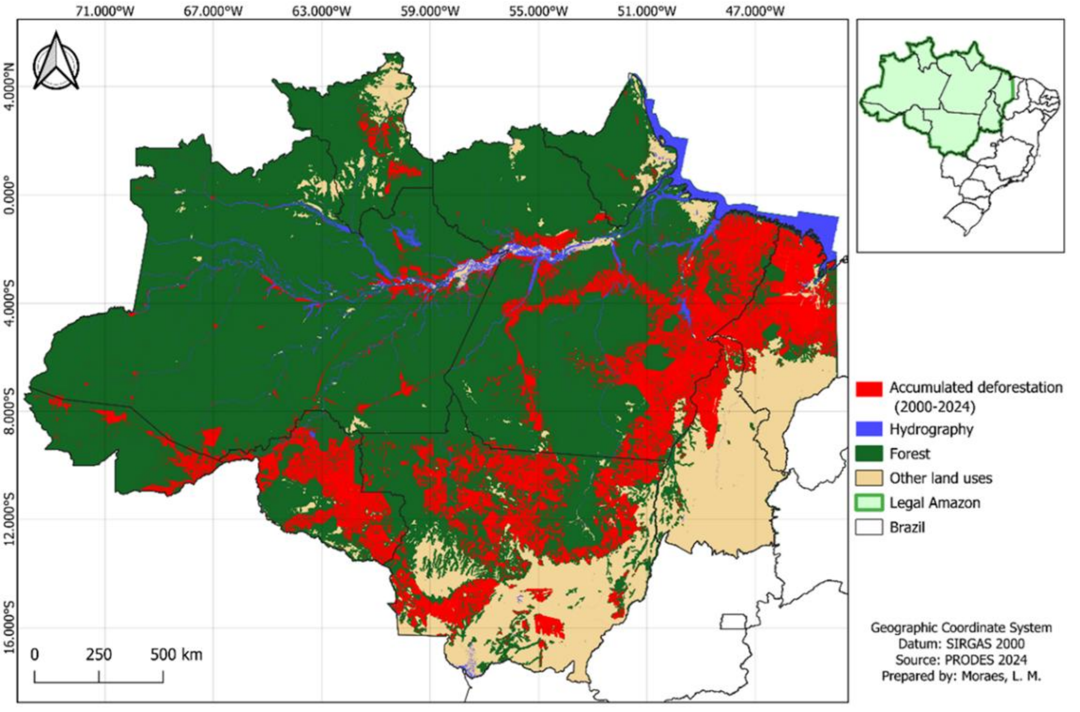

Figure 2. Representation of forested, non-forested, and deforested areas in the Brazilian Amazon up to the 2024, characterizing the "Deforestation Arc of the Amazon" (Prepared using the 2024 database from the Satellite Monitoring Project of Deforestation in the Legal Amazon, PRODES).

In this context, initiatives such as the sustainable management of socio-biodiversity products, reforestation with native species, the intensification of agroforestry systems, and sustainable livestock farming stand out as promising solutions to balance conservation and productivity. Livestock, a central activity for the economy of many municipalities in the region, holds great potential for improvement through practices such as pasture recovery and integrated crop-livestock-forestry systems (ICLF), which contribute to increased productivity, forest conservation, and the empowerment of small and medium-sized rural producers (Badari et al., 2020; Bueno et al., 2021; Lapola et al., 2023; Ramineh et al., 2023).

2.2. Economic potential and sustainable practices

In addition to its ecological value, the Brazilian Amazon also holds significant productive potential. Despite the challenges related to land use, such as the conversion of forests into agricultural areas, the region offers concrete opportunities for sustainable practices that reconcile environmental conservation, social inclusion, and economic viability (Table 1). The "Arc of Deforestation," although characterized by intense pressure, also reveals strategic areas where vulnerability can be transformed into productive and ecological recovery (Bueno et al., 2021; Gomes et al., 2024).

Sociobiodiversity products, such as guaraná (*Paullinia cupana*), buriti (*Mauritia flexuosa*), cacao (*Theobroma cacao*), and açaí (*Euterpe oleracea*), illustrate how income generation can be combined with environmental preservation, directly benefiting local communities (Cunha & Costa, 2020; Gomes et al., 2021). Guaraná, when cultivated sustainably, holds economic and cultural importance for smallholder farmers (Vignoli et al., 2022). Buriti, characteristic of floodplain areas, is used in the production of food, cosmetics, and oils, and its cultivation contributes to the regeneration of degraded areas (Ibiapina et al., 2022).

Cacao and açaí, widely cultivated in agroforestry systems, contribute to the recovery of degraded soils, biodiversity conservation, and income generation, especially in Pará and among riverside communities. Additionally, black pepper (*Piper nigrum*) demonstrates the integration of traditional practices and technological innovation, establishing Tomé-Açu as a productive and sustainable hub (Cruz & Rocha, 2019; Cunha & Costa, 2020; Paracampo et al., 2022).

However, Amazon also hosts agricultural crops with higher environmental impact, such as soybean (*Glycine max*) and oil palm (*Elaeis guineensis*). Driven by high global demand, soybean has become one of the main economic activities in the region, requiring more sustainable practices (Brito et al., 2021; Bueno et al., 2021). Oil palm, although holding potential for economic diversification, often contributes to soil degradation and forest fragmentation due to its unregulated expansion, highlighting the need for proper management (Gomes et al., 2021).

Table 1
Examples of sustainable land-use practices in the Brazilian Amazon and their associated benefits

Sustainable practice or product	Production system	Main benefit	Reference
Guaraná (*Paullinia cupana*)	Traditional cultivation	Income and cultural value for local farmers	Cunha & Costa (2020); Vignoli et al. (2022)
Buriti (*Mauritia flexuosa*)	Extractivism; agroindustrial use	Multiple uses and floodplain restoration	Ibiapina et al. (2022)
Cacao (*Theobroma cacao*)	Agroforestry system (AFS)	Soil recovery and biodiversity	Schroth et al. (2015); Gomes et al. (2021);
Açaí (*Euterpe oleracea*)	Agroforestry system (AFS)	Income, conservation, and social inclusion	Paracampo et al. (2022); Gomes et al. (2024)
Black pepper (*Piper nigrum*)	Integrated agriculture	Traditional knowledge combined with innovation	Cruz & Rocha (2019); Cunha & Costa (2020)
Soybean (*Glycine max*)	Intensive agriculture	High profitability; requires sustainable practices	Brito et al. (2021); Bueno et al. (2021)
Oil palm (*E. guineensis Jacq.*)	Industrial perennial cultivation	Economic potential; risk if poorly managed	Gomes et al. (2021)
Sustainable livestock	Integrated systems	High productivity without land expansion; natural resource conservation	Bueno et al. (2021); Lapola et al. (2023); Ramineh et al. (2023)

In addition to agricultural and extractive crops, livestock farming holds a strategic position in the Amazonian economy, serving as the productive base for many municipalities. The sector has expanded its sustainable potential through practices such as the restoration of already deforested areas and crop-livestock-forestry integration (CLFI), which enhances productivity, preserves natural resources, and strengthens the livelihoods of small and medium-sized farmers without the need to clear new land (Bueno et al., 2021; Lapola et al., 2023; Ramineh et al., 2023).

Understanding the climatic, ecological, and sociocultural specificities of the Amazon is essential for adapting agricultural management strategies to the local context. Factors such as ecosystem diversity, rainfall regimes, soil types, and traditional livelihoods directly influence the effectiveness of sustainable practices. This integrated approach enables the region to continue playing a crucial role in global climate regulation, establishing itself as a model of development that combines environmental conservation, social inclusion, and economic viability.

3. Climatic conditions and soil dynamics in the Amazon

3.1. Climatic classification of the Amazon

The Brazilian Amazon is widely recognized for its tropical climate, which plays a central role in sustaining its biodiverse ecosystems and in global climate regulation (Artaxo et al., 2022). According to the Köppen climate classification system, widely used for its global applicability, the region is predominantly classified as type A climate, characterized by high annual rainfall, elevated temperatures, and high relative humidity (Alvares et al., 2013; Andrade et al., 2017; Cui et al., 2021).

In the state of Pará, three climatic subtypes stand out: humid tropical (Af), tropical monsoon (Am), and tropical with a dry season (Aw). The Af climate features well-distributed rainfall throughout the year, while the Am and Aw climates have distinct rainy and dry seasons. This climatic diversity shapes the distribution of ecosystems and the functioning of natural systems, such as water and energy cycles (Alvares et al., 2013; Andrade et al., 2017; Hoffmann et al., 2018). Table 2 summarizes the main characteristics of these climatic subtypes.

3.2. Influence of the tropical climate on soil

The climatic conditions of the Amazon, characterized by high humidity and elevated temperatures, exert a strong influence on the region's soils. These conditions favor intense microbial activity, which is essential for organic matter decomposition and nutrient cycling (Flores et al., 2020; Buscardo et al., 2021). However, the same conditions also accelerate leaching and erosion processes, especially in unprotected soils, resulting in the loss of fertility in deforested or poorly managed areas (Tahat et al., 2020).

Table 2
Climatic characteristics of tropical climates in Pará

Climate	Temperature range	Annual average temperature	Annual total average precipitation	Rainy season	Dry season	Geographic distribution
Af	24° C – 27 °C	> 26.7 °C	2.000 to 3.000 mm	December to May	Not defined	28.4%
Am	25 °C – 30 °C	25.8 °C – 29 °C	≈ 2.850 mm	December to May	July to August	66.6%
Aw	22 °C – 28 °C	24 °C – 27 °C	≈ 1.600 mm	December to May	June to November	4.9%

Climatic types: humid tropical (Af), tropical monsoon (Am), and tropical with a dry season (Aw). Adapted from Alvares et al. (2013), Andrade et al. (2017), and Hoffmann et al. (2018).

The interaction between tropical climate and human activities can increase soil susceptibility to degradation. In deforested areas, the reduction of vegetation cover exposes the soil to intense rainfall, which can result in the removal of the surface layer rich in organic matter. These processes tend to reduce soil fertility and resilience, especially in areas with inadequate management, highlighting the importance of conservation practices as a strategy to mitigate these effects (Figure 3) (Hu et al., 2021; Gatti et al., 2021).

Moreover, extreme weather events, such as prolonged droughts and severe floods, exacerbate the negative impacts on soil dynamics by altering nutrient availability and hydrological cycles. When combined with degradation caused by deforestation and land conversion, these events underscore the urgency of sustainable management practices. Such practices should prioritize the resilience of Amazonian soils, reducing their vulnerability to climatic impacts and uncontrolled human activities (Deng et al., 2020; Patel et al., 2021).

Understanding these interactions between climate, soil, and human activities is essential for developing integrated strategies that reconcile sustainable land use with environmental conservation. These actions become even more relevant given the crucial role Amazonian soils play as global reservoirs of carbon and nitrogen key elements in climate regulation (Hou, 2021; Wang et al., 2023). Thus, management practices that preserve or enhance these stocks can contribute to mitigating the impacts of climate change and ensuring the functionality of Amazonian ecosystems.

4. Soil carbon and nitrogen stocks

4.1. Importance of carbon and nitrogen stocks

Carbon and nitrogen cycles are essential for global climate regulation, connecting processes such as respiration, decomposition, and chemical transformations that link soil organic matter (SOM), the atmosphere, and the oceans (Lal et al., 2021). In the Brazilian Amazon, soils play a crucial role in retaining these elements, due to the region's high biodiversity and the continuous input of organic residues from native vegetation (Gomes et al., 2019). Although distinct, these cycles are closely interrelated, as nitrogen transformations through processes such as fixation, mineralization, and denitrification directly influence soil fertility and GHG emissions (Liu et al., 2024).

In addition to their role in fertility, soil carbon and nitrogen stocks are fundamental for mitigating climate change. The carbon stored in the soil functions as a critical reservoir, reducing atmospheric carbon dioxide (CO_2) concentrations, while nitrogen regulates primary production and the decomposition of organic matter, balancing the functioning of terrestrial ecosystems. These stocks support both ecosystem productivity and their resilience to climate change (Dai et al., 2020).

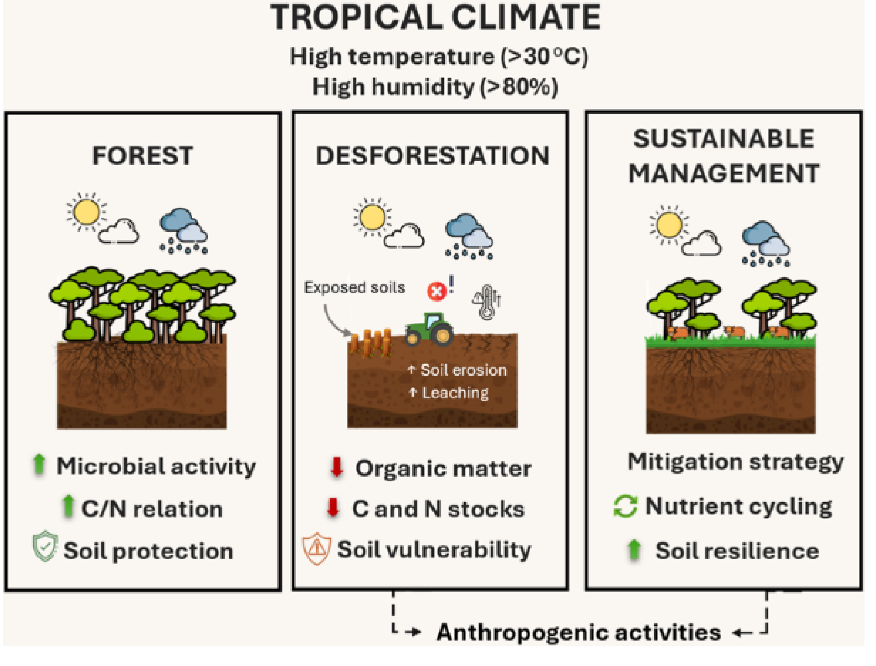

Figure 3. Influence of tropical climate and anthropogenic activities on soil dynamics in the Amazon. Adapted from Flores et al., 2020; Deng et al., 2020; Buscardo et al., 2021; Tahat et al., 2020; Hu et al., 2021; Patel et al., 2021; Hou, 2021; Wang et al., 2023.

The vulnerability of these stocks is directly linked to land-use changes and inadequate management practices. Tropical soil, such as those in the Amazon, have a high capacity for carbon storage. However, when forests are converted into agricultural areas or pastures without proper technical criteria, there is a greater risk of degradation and loss of organic matter. On the other hand, studies indicate that well managed pastures can maintain carbon stocks comparable to those of native forests, demonstrating that sustainable management is crucial for preserving this ecological function of soils (Midwood et al., 2021; Nagano et al., 2023; Azevedo et al., 2024).

4.2. Factors influencing carbon and nitrogen stocks

The stability and dynamics of soil carbon and nitrogen stocks are governed by a combination of physical, chemical, biological, climatic, and management factors. These factors interact and directly influence the processes of accumulation, decomposition, retention, and loss of these elements within the soil profile. The way these mechanisms operate depends on the intrinsic characteristics of the edaphic environment and the land-use practices adopted, affecting both the magnitude and the stability of stocks over time (Table 3).

Among the physical factors, soil texture plays a central role. In the Amazon, both clayey and sandy soils are widely distributed, influencing carbon and nitrogen retention in different ways. Clayey soils, more common in central and eastern areas of the Amazon basin, have a greater capacity for carbon retention due to the high specific surface area of clay particles, which promotes the formation of stable aggregates and reduces the decomposition of organic matter (Flores et al., 2020; Quesada et al., 2020).

In contrast, sandy soils, predominant in transition zones and in eastern Amazonia, exhibit lower stability and reduced capacity to retain carbon and nitrogen. This is due to their lower specific surface area and limited ability to form stable aggregates, making them more susceptible to erosion and rapid mineralization of organic matter (de Oliveira et al., 2022; Liu et al., 2022). These characteristics result in greater vulnerability to carbon and nitrogen losses, especially in poorly managed agricultural systems (Okebalama et al., 2021).

Climatic conditions, such as temperature and humidity, also exert significant influence. The hot and humid climate typical of the Amazon accelerates the decomposition of soil organic matter (SOM), intensifying the release of CO_2 and nitrous oxide (N_2O). In addition, these factors promote the mineralization of particulate organic carbon (POC), which is more susceptible to degradation. In contrast, mineral-associated organic carbon (MAOC) is more stable and plays a critical role in long-term carbon storage (Midwood et al., 2021; Nagano et al., 2023), although it occurs in lower proportions than POC in Amazonian soils (Cotrufo & Lavallee, 2022).

Vegetation cover plays a key role in carbon and nitrogen stocks. Native forests have a greater capacity for carbon and nitrogen accumulation due to the constant input of organic residues and the stability of biogeochemical cycles. The conversion to agricultural or pasture systems can impact these stocks in variable ways, depending on the practices adopted. Well-managed agricultural systems and pastures have shown potential to conserve or recover part of these stocks (Azevedo et al., 2024; Rego et al., 2023; Zeferino et al., 2023).

Table 3
Main physical, climatic, ecological, and management factors influencing soil carbon (C) and nitrogen (N) stocks in the Amazon region

Category	Factor	Effect on C and N stocks	Reference
Physical	Soil texture	Clay retains more C and N; sand increases vulnerability to erosion and mineralization	Flores et al. (2020); Quesada et al. (2020); de Oliveira et al. (2022); Liu et al. (2022)
	Topography	Flat areas accumulate organic matter; slopes are prone to erosion	Hu et al. (2021)
	Hydrology	Poor drainage promotes C accumulation; well-drained soils enhance mineralization	Ye et al. (2019)
Climatic	Tropical climate	High temperature and humidity accelerate decomposition and GHG emissions	Midwood et al. (2021); Cotrufo & Lavallee (2022); Nagano et al. (2023)
	Extreme events	Droughts and floods destabilize stocks and increase emissions	Li et al. (2024)
Ecological	Carbon forms	POC is more labile and easily degraded; MAOC is more stable but less abundant	Midwood et al. (2021); Cotrufo & Lavallee (2022); Nagano et al. (2023)
	Soil biodiversity	Enhances C and N cycling and stabilization; degraded by intensive inputs and machinery	Lal (2019)
Management	Vegetation cover	Forests enhance stock accumulation; land conversion may conserve or deplete stocks	Azevedo et al. (2024); Rego et al. (2023); Zeferino et al. (2023)
	Land use practices	Sustainable management conserves stocks; poor practices increase erosion and nutrient loss	Kooch et al. (2021); Lal (2019)

Notes: C - carbon; N - nitrogen; GHG – greenhouse gases; POC - particulate organic carbon; MAOC - mineral associated organic carbon.

On the other hand, vegetation removal in degraded areas favors erosion and nutrient loss (Kooch et al., 2021). Topography also influences this process, as flat areas tend to accumulate more organic matter, while slopes are more prone to soil loss (Hu et al., 2021). Local hydrology regulates SOM decomposition and soil gas emissions. Poorly drained soils tend to accumulate carbon, whereas well-drained soils favor its mineralization (Ye et al., 2019). Extreme climate events, such as droughts and floods, can further intensify GHG emissions and reduce stock stability (Li et al., 2024).

Finally, soil biodiversity, including macro and microfauna, is crucial for biogeochemical functioning and carbon sequestration. Soil organisms actively participate in the decomposition of organic matter and carbon stabilization, while inadequate management practices, such as excessive use of machinery and chemical fertilizers, can degrade this biodiversity and compromise long-term carbon stocks (Lal, 2019).

4.3. Impacts of land use on carbon and nitrogen stocks

Land-use changes directly affect soil carbon and nitrogen stocks, depending on the type of management and practices adopted. Under inadequate conditions, such changes contribute to the loss of soil organic matter (SOM) and increased GHG emissions (Ahirwal et al., 2021). Stocks also vary with soil depth, most assessed in the 0–30 cm and 0–100 cm layers, which provide different perspectives on carbon sequestration and nutrient retention capacity (IPCC, 2019; Azevedo et al., 2024).

In the Amazon, Azevedo et al. (2024) reported carbon stocks of 77.1 Mg C ha^{-1} in native forests and 67.6 Mg C ha^{-1} in well-managed pastures, with no statistically significant difference, demonstrating that proper management can preserve carbon stocks even in converted areas. In contrast, agricultural systems with bare soil, such as intensive pepper cultivation, showed significantly lower stocks (36.4 Mg C ha^{-1}), reflecting the effects of vegetation removal, soil disturbance, and intensive input use on organic matter decomposition (Hu et al., 2021; Leul et al., 2023).

In the Cerrado biome, the conversion of native areas to extensive pastures was associated with a 37.3% reduction in carbon stocks in the 0–30 cm layer, while conversion to rainfed agricultural systems resulted in a 30.3% loss. On the other hand, irrigated agricultural systems, when properly managed, promoted an increase of up to 34% in carbon stocks, highlighting that land use type, and especially the management practices adopted, can either mitigate or intensify the impacts of land-use conversion (Dionizio et al., 2020).

Agrosilvopastoral and agroforestry systems stand out as viable alternatives for restoring carbon and nitrogen stocks in degraded areas. Lustosa Filho et al. (2024) observed that silvopastoral systems in the Amazon exhibited higher carbon and nitrogen stocks in sandy soils (0–100 cm) compared to conventional pastures, while 25% shading in silvopastoral systems provided an additional carbon sequestration of 1.67 Mg C ha^{-1} yr^{-1}. Moreover, agrosilvopastoral systems in the Cerrado restored carbon stocks over 20 years, positioning themselves as more sustainable alternatives to extensive pastures (Freitas et al., 2020).

Santos et al. (2019) reported that pasture management with *Urochloa brizantha* cultivars (Arapoti and Xaraés) in the Atlantic Forest significantly increased carbon and nitrogen stocks down to 100 cm. In that study, total carbon stocks at 100 cm were 97.3 Mg C ha^{-1} in native vegetation, 116.2 Mg C ha^{-1} in the Arapoti cultivar, and 119.4 Mg C ha^{-1} in the Xaraés cultivar. In the 0–30 cm layer, the stocks were 49.3 Mg C ha^{-1} in native vegetation, 61.2 Mg C ha^{-1} in Arapoti, and 66.6 Mg C ha^{-1} in Xaraés. These results indicate that well-managed pastures can increase soil carbon stocks, partially offsetting losses associated with deforestation. Additionally, sustainable intensification practices, such as agricultural intercropping, have shown promise in more fragile biomes such as the Caatinga. Tonucci et al. (2023) demonstrated that agropastoral systems composed of forage species and crops adapted to the semiarid climate were able to maintain soil carbon stocks nearly equivalent to those of native areas in both the 0 – 30 cm and 0 – 100 cm layers. These findings reinforce the role of integrated practices as viable strategies for soil conservation, GHG emission reduction, and ecological resilience in regions vulnerable to desertification. Similar results were observed in the Amazon by Monteiro et al. (2024), who highlighted the potential of integrated crop-livestock-forestry (ICLF) systems to increase soil carbon and nitrogen stocks, promote more sustainable grain and forage production, and offset GHG emissions. The study showed that, over four years, integrated systems incorporated more than 270 kg N ha^{-1} and produced three times more edible protein for human consumption compared to conventional systems.

The data presented in Table 4 illustrates the variation in carbon and nitrogen stocks across different land-use systems and soil depths. In general, native forests tend to show the highest stocks, especially in biomes such as the Cerrado and the Amazon.

Table 4
Soil carbon and nitrogen stocks (Mg ha^{-1}) at 0 – 30 cm and 0 – 100 cm depths under different land uses in Brazil

Land use	Description	Soil	SCS (0 -30 cm)	SNS (0 -30 cm)	SCS (0 - 100 cm)	SNS (0 - 100 cm)	Reference
Amazon							
Native Forest	Selective logging, no suppression, 25 years	Oxisol	77.1	6.3	137.5	13.8	Azevedo et al. (2024)
Native Forest	Adjacent area to silvopastoral systems used as a reference	Entisol	18.0	-	45.0	-	Lustosa Filho et al. (2024)
Agriculture	*Black pepper* (*Piper nigrum*) fields established after pasture (2010 – 2014)	Oxisol	36.4	3.0	63.9	6.0	Azevedo et al. (2024)
Nominal Pasture[1]	*U. brizantha* cv. Marandu, established between 1988 – 2007 with burning and cassava cultivation	Oxisol	67.6	5.7	144.8	13.3	Azevedo et al. (2024)
Nominal Pasture[1]	*M. maximus* cv. Mombaça + weeds, established in 2013	Entisol	23.0	-	59.0	-	Lustosa Filho et al. (2024)
Intensive Pasture	*M. maximus*, established in 2006, high productivity	Entisol	17.0	-	44.0	-	Lustosa Filho et al. (2024)
Silvopastoral System	*M. maximus* + tree species with 25%, 50%, or 75% shading	Entisol	27.3	-	52.0	-	Lustosa Filho et al. (2024)
Caatinga							
Native Forest	Area of native vegetation with no deforestation since the 1980s.	Inceptisol	54.3	3.1	76.4	6.3	Tonucci et al. (2023)
Agroforestry System	Native vegetation + sorghum/millet + pigeon pea + *M. maximus* cv. Massai, established after native vegetation removal in 2016 – 2017.	Inceptisol	23.8	1.0	66.4	2.7	Tonucci et al. (2023)
Agropastoral System	Established after native vegetation removal in 2016 – 2017	Inceptisol	51.9	3.9	75.4	7.9	Tonucci et al. (2023)
Cerrado							
Native Forest	Intact area, no anthropogenic intervention	Oxisol/ Entisol	51.0	-	82.5	-	Dionizio et al. (2020)
Native Forest	"Cerradão" vegetation, no anthropogenic intervention	Oxisol	109.2	7.9	-	-	Freitas et al. (2020)
Agriculture	Annual crops established after native vegetation or pastures; rainfed	Oxisol/ Entisol	32.2	-	57.4	-	Dionizio et al. (2020)
Agriculture	Annual crops established after native vegetation or pastures; irrigated	Oxisol/ Entisol	45.5	-	78.1	-	Dionizio et al. (2020)
Intensive Pasture	*U. brizantha* introduced in 2014, after conversion of degraded areas	Oxisol	65.5	4.4	-	-	Freitas et al. (2020)
Degraded Pasture	*U. brizantha* established after native vegetation removal in 1994	Oxisol	58.1	4.0	-	-	Freitas et al. (2020)
ILPF System	Maize, eucalyptus, and *U. brizantha* introduced in 2014, after conversion of degraded areas	Oxisol	70.1	4.5	-	-	Freitas et al. (2020)
Atlantic Forest							
Native Forest	Intact area, no human intervention	Argissolo	49.3	4.0	97.3	7.8	Santos et al. (2019)
Intensive Pasture	*U. brizantha* cv Arapoti, established after deforestation in 2000	Argissolo	61.2	5.4	116.2	9.8	Santos et al. (2019)
Intensive Pasture	*U. brizantha* cv Xaraés, established after deforestation in 2000	Argissolo	66.6	4.6	119.4	8.7	Santos et al. (2019)

Notes: SCS – Soil Carbon Stock; SNS – Soil Nitrogen Stock. [1]Nominal pasture: sustainably managed area, without degradation, but without significant improvements in management (IPCC, 2006; de Oliveira et al., 2022).

However, in some regions, well-managed pastures have surpassed the values observed in native areas. Sustainable management practices, such as agrosilvopastoral systems, have shown high potential to restore stocks in degraded areas. On the other hand, conventional land uses and the absence of proper management are often associated with greater losses, particularly in the top-soil layer.

5. Greenhouse gas emissions

Greenhouse gases (GHGs) are atmospheric components that absorb and emit radiation within the infrared spectrum, creating a natural phenomenon known as the greenhouse effect, which is essential for maintaining life on Earth (Lian et al., 2019).
However, human activities such as fossil fuel combustion, deforestation, and intensive agricultural practices have significantly increased the concentration of these gases, intensifying global warming and contributing to climate change (Lobus et al., 2023). The main GHGs include CO_2, CH_4, N_2O, fluorinated gases, and water vapor (Pacheco et al., 2019). CO_2 accounts for 64% of the increase in heat retained in the atmosphere (Figure 4), making it the main con-

tributor to global warming (WMO, 2023). To facilitate comparisons among different GHGs, the concept of carbon dioxide equivalent (CO_2eq) is used, which expresses the emissions of other gases in terms of their global warming potential (GWP) relative to CO_2 (IPCC, 2019).

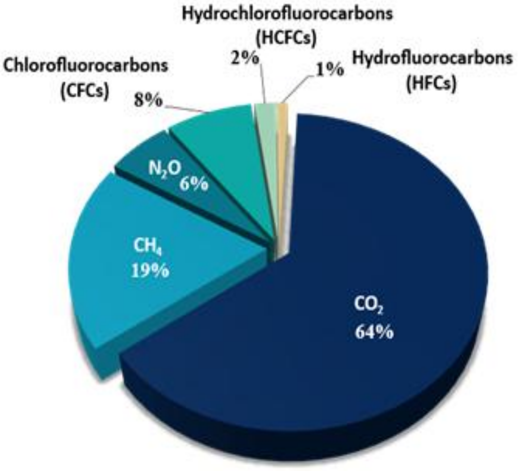

Figure 4. Emissions of major greenhouse gases from the pre-industrial era to 2022 (Adapted from the GHG Bulletin, WMO, 2023).

Despite its higher atmospheric concentration, CO_2 has a lower global warming potential (GWP) compared to CH_4 and N_2O, which are 27 and 273 times more potent, respectively, over a 100-year period (IPCC, 2019). However, CO_2 has a much longer atmospheric lifetime, potentially persisting for decades to centuries, whereas CH_4 and N_2O remain in the atmosphere for approximately 12 and 114 years, respectively. This increase in GHG concentrations is directly linked to rising global temperatures, changes in climate patterns, sea level rise, and the increased frequency of extreme events (Hanna & Hall, 2020).

In this context, a detailed analysis of GHG emissions by sector is essential to identify the main contributors and to develop targeted mitigation strategies. The energy sector, responsible for about one-third of global GHG emissions, stands out due to the burning of fossil fuels for electricity generation and transportation (Lamb et al., 2021). The industrial sector, in turn, accounts for approximately 30% of global emissions, mainly from energy-intensive processes in the metallurgical and petrochemical industries (Chien & Krumins, 2023). In agriculture and livestock, emissions are primarily derived from enteric fermentation, manure management, fertilizer use, and rice cultivation (Chiriacò et al., 2021).

In Brazil, GHG emissions are predominantly concentrated in the land-use change and forestry sector, which accounts for 1.12 billion tons of CO_2eq (Figure 5a). This total is primarily driven by deforestation in the Amazon and Cerrado biomes (SEEG). Agriculture and livestock also play a significant role, contributing 606.26 million tons of CO_2eq, of which 63% originate from enteric fermentation and 30% from soil management (Figure 5b). Other relevant sectors include energy (18%), solid waste (4%), and industrial processes (3%) (SEEG, 2022).

5.1. GHG emission dynamics and influencing factors

5.1.1. Soil CO_2 emissions

Soil CO_2 emissions are an essential component of the carbon cycle, occurring mainly through the decomposition of organic matter and root respiration (Abreu et al., 2024). During photosynthesis, plants capture CO_2 from the atmosphere and produce organic matter, which, when decomposed, releases CO_2 back into the atmosphere, completing the cycle. This process is influenced by biological, physical, and chemical factors, as well as by soil management practices (Jones et al., 2019; Soares & Rousk, 2019; Lal et al., 2021).

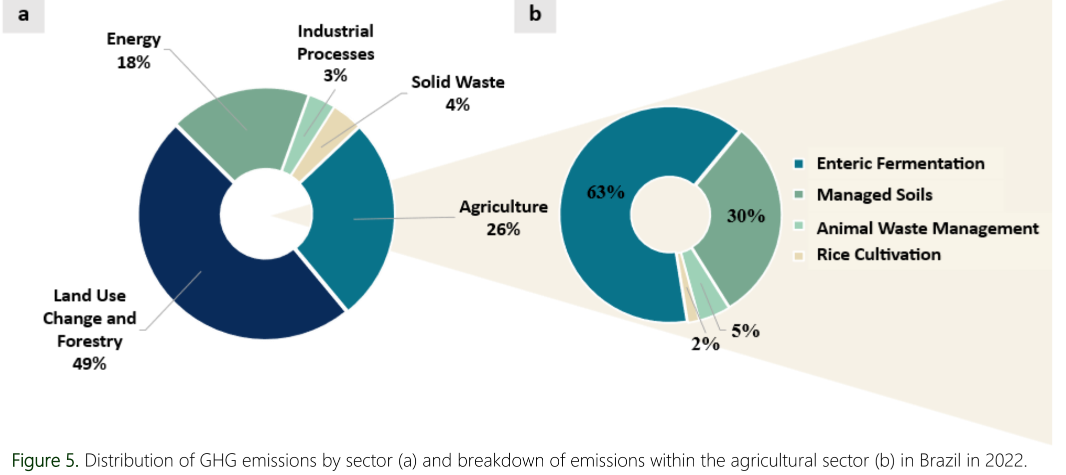

Figure 5. Distribution of GHG emissions by sector (a) and breakdown of emissions within the agricultural sector (b) in Brazil in 2022. Adapted from SEEG (2022).

Among the biological factors, microbial activity and root respiration play a fundamental role in CO_2 release. These processes can be intensified by agricultural practices that increase nutrient availability, such as fertilizer application, or alter soil structure, such as mechanization (Segnini et al., 2019; Chen et al., 2021). However, conservation practices like no-tillage, which avoid soil disturbance and exposure of organic matter to oxygen, and promote a higher proportion of micropores, have the potential to stabilize carbon stocks and reduce emissions.

Soil physical factors, such as texture, structure, and moisture, directly influence CO_2 emissions. Clay soil, for instance, retains more moisture, which can enhance microbial activity (Miller et al., 2020). Land-use and forest changes convert carbon sinks into emission sources, with global estimates of 1.36 ± 0.42 Pg C year^{-1} between 2009 and 2018 (Gasser et al., 2020). In Brazil, such conversions have reduced soil carbon stocks and increased emissions, whereas agroforestry systems (Rosa & Neto, 2019) and/or recovered or well-managed pastures have shown greater efficiency in carbon retention (de Oliveira et al., 2022; Azevedo et al., 2024).

Chemical factors, such as soil pH, nutrient availability, and the presence of heavy metals, directly affect CO_2 emissions. Soils with neutral or slightly acidic pH exhibit higher microbial activity, whereas highly acidic or alkaline soils inhibit organic matter decomposition (Bramble et al., 2019; Shaaban et al., 2019). Although fertilizer applications can stimulate microbial activity, it may also enhance CO_2 release due to increased organic matter decomposition.

Sustainable management practices have shown great potential in reducing CO_2 emissions and enhancing the soil's carbon sequestration capacity. No-tillage systems, for example, improve soil structure and promote a more stable environment, thereby reducing long-term emissions. Studies indicate that long-term no-tillage systems exhibit greater carbon retention and soil resilience, particularly due to improvements in soil moisture and porosity (Santos et al., 2019).

In addition, well-managed pastures through practices such as rotational grazing, balanced fertilization, and proper stocking rate control can significantly increase soil carbon stocks. Compared to degraded pastures, these practices help stabilize soil carbon, reduce CO_2 emissions, and enhance the sustainability of agricultural production (Segnini et al., 2019). Such strategies not only mitigate environmental impacts but also improve soil fertility and production efficiency.

5.1.2. CH_4 emissions

Methane (CH_4) production in soils occurs predominantly through methanogenesis, an anaerobic process carried out by methanogenic Archaea. This process plays a crucial role in the carbon cycle, taking place both naturally and under human influence. Methanogenesis can be divided into two main pathways: acetoclastic methanogenesis, in which acetate (CH_3COOH) is converted into CH_4 and CO_2; and hydrogenotrophic methanogenesis, in which CO_2 is reduced to CH_4 using hydrogen (H_2) as an electron donor (Dean et al., 2018; Conrad, 2020; Alves et al., 2022).

In addition to CH_4 production, this gas can be oxidized back to CO_2 by methanotrophic microorganisms under aerobic conditions or by ammonia-oxidizing bacteria. These processes, known as methanotrophy, are critical for maintaining the CH_4 balance in soils, acting as a counterbalance to its production (Zhang et al., 2019; Dizon et al., 2023). Thus, CH_4 exchange in soils depends on the dynamic balance between its production (methanogenesis) and its oxidation (methanotrophy), which is regulated by factors such as aerobic or anaerobic conditions, substrate availability, and the activity of specialized microbial communities.

Flooded agricultural systems, such as rice paddies, are major sources of CH_4 due to the anaerobic conditions created by prolonged waterlogging (Gu et al., 2022). Management practices such as mid-season drainage can reduce these emissions by temporarily introducing oxygen into the soil, thereby inhibiting methanogenic activity (Yan et al., 2019). Furthermore, the conversion of forests to pastures tends to increase CH_4 emissions, while management strategies that reduce organic matter inputs can help mitigate them (Lage Filho et al., 2023).

Lage Filho et al. (2023), evaluating the impacts of land use, temperature, and nitrogen application on CH_4 emissions in the Eastern Amazon, found that the highest emissions occurred in pasture soils, reaching values of 470 ng CH_4 g^{-1} dry soil. These high values were attributed to enhanced methanogenic microbial activity under favorable conditions, such as greater organic matter availability and soil moisture. In addition, they found that soil warming above 30 °C can reduce CH_4 emissions, whereas nitrogen addition may either increase or decrease emissions depending on the dose and soil type.

Despite these findings, recent evidence indicates that pastures can also act as CH_4 sinks depending on management. Alves et al. (2022) showed that pastures harbor more complex and responsive methanogenic communities, with higher early CH_4

emissions under favorable conditions. Moreover, Souza et al. (2021) demonstrated that maintaining grass cover in pastures significantly reduced the abundance of methanogenic archaea and increased CH_4 uptake by up to 35%. These findings highlight the critical role of pasture management in determining whether they function as sources or sink of methane. Another study examined how nitrogen fertilizer sources and application rates affect CH_4, CO_4, and N_2O fluxes in warm-season pastures. The results showed that while nitrogen fertilization significantly increased cumulative N_2O and CO_2 emissions, it had no significant effect on CH_4 emissions, suggesting that CH_4 fluxes are more closely linked to soil structure and its water retention capacity (Corrêa et al., 2021).

5.1.3. N_2O emissions

The production of N_2O in the soil is related to the processes of nitrification and denitrification (Figure 6). In nitrification, microorganisms convert ammonia (NH_3) into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-), releasing N_2O as a byproduct (Figure 6a). In denitrification, which occurs under anaerobic conditions, nitrate is sequentially reduced to molecular nitrogen, with N_2O as an intermediate (Figure 6b) (Prosser et al., 2019; Wang et al., 2021).

The use of mineral and organic fertilizers increases nitrogen availability in the soil, promoting the formation of N_2O through nitrification and denitrification processes (Kudeyarov, 2020). In compacted or poorly drained soils, emissions are even higher due to the intermediate oxygenation conditions, which favor incomplete nitrate reduction (Prosser et al., 2019; Conrad, 2020). Additionally, the presence of available organic carbon enhances denitrifying activity, contributing to higher N_2O emission rates (Liu et al., 2022).

The increase in the amount of nitrogen fertilizers used during land use changes significantly alter N_2O emissions. Lage Filho et al. (2022) found that N_2O emissions were higher in agricultural soils compared to forest and pasture areas, and that soil temperature increases further elevated these emissions. The contribution of denitrification to N_2O production increases with temperature in some soil types, while autotrophic nitrification is also influenced by temperature (Zhang et al., 2021).

Studies conducted in the Brazilian Amazon confirm the influence of nitrogen fertilization on N_2O emissions in tropical pastures. Nascimento et al. (2021) observed that *Urochloa brizantha* pastures fertilized with 40 and 80 kg N ha^{-1}, using urea or ammonium sulfate, exhibited N_2O emission peaks between 4 and 7 days after application. Emission fluxes were highest in the treatments with 80 kg N ha^{-1}, while the lowest occurred in the control and the treatment inoculated with *Azospirillum brasilense*. In all fertilizer treatments, the emission factors were below 0.35%, lower than the IPCC default value of 1%. These findings highlight the importance of selecting appropriate nitrogen sources and application rates to support sustainable management in tropical systems.

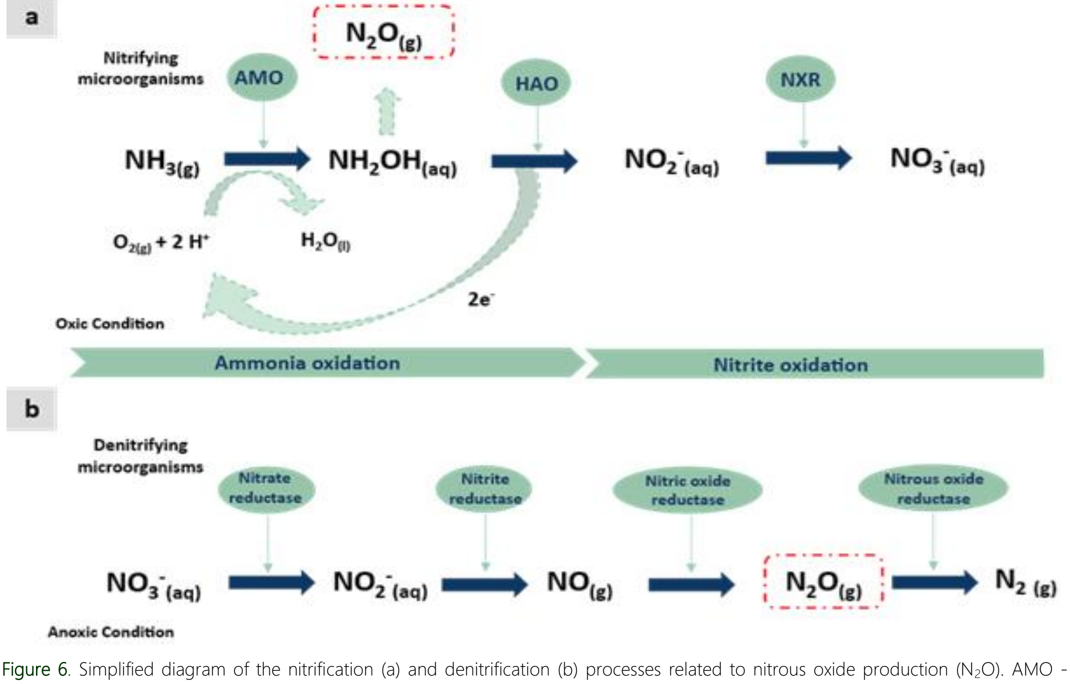

Figure 6. Simplified diagram of the nitrification (a) and denitrification (b) processes related to nitrous oxide production (N_2O). AMO - Ammonia monooxygenase; HAO - Hydroxylamine oxidoreductase; NXR - Nitrite oxidoreductase. Adapted from Prosser et al. (2019), Wang et al. (2021), and Zhang et al. (2021).

Management practices, such as crop rotation and soil preparation (conventional tillage or no-tillage), directly influence nitrogen dynamics in the soil and, consequently, N_2O emissions (Machado et al., 2021). Climatic conditions, including soil temperature and moisture, also strongly affect N_2O fluxes. In warm and humid environments, microbial activity tends to increase, leading to higher emissions (Corrêa et al., 2021). Although such conditions may occur under no-tillage systems, the absence of soil disturbance, maintenance of aggregate structure, and reduced soil aeration help offset the effects of increased moisture, thereby reducing N2O emissions. Understanding the interaction among these factors is essential for developing sustainable agricultural practices capable of mitigating N2O emissions and minimizing the climate impacts of agricultural activities.

6. Sustainable solutions and future challenges

In response to the impacts of climate change, institutions and initiatives have been established to bridge the gap between science and public policy. The Intergovernmental Panel on Climate Change (IPCC), founded in 1988, aims to provide scientific assessments of climate risks and guide mitigation and adaptation strategies (Kohler & Rockman, 2020). At COP21, held in Paris in 2015, 195 countries committed to limiting global warming to below 2 °C, with efforts to restrict it to 1.5 °C (Allan et al., 2023). These international agreements directly influence Brazilian policies related to sustainable land use and climate change mitigation.

In Brazil, the Amazon Fund, established in 2008, supports projects focused on deforestation prevention, monitoring, and control, promoting conservation and sustainable use of forests in the Legal Amazon (Correa et al., 2020). Another key initiative is the Low Carbon Agriculture Plan (ABC Plan), launched in 2010, which encourages low-carbon agricultural practices such as pasture recovery, integrated crop-livestock-forestry systems (ICLFS), no-tillage, biological nitrogen fixation, planted forests, and animal waste management (Quintão et al., 2021; Piao et al., 2021).

Land-use changes directly affect regional climate by altering rainfall distribution and increasing surface temperatures. Deforestation reduces evapotranspiration, can raise temperatures by up to 3 °C, and disrupt surface atmospheric circulation patterns (Hong et al., 2022; Rodrigues et al., 2022). In the Amazon, activities such as logging and the subsequent conversion of natural areas into agricultural lands have jeopardized carbon and nitrogen stocks, biodiversity, and ecological functioning (Azevedo et al., 2024). Addressing these challenges requires integrated strategies that reconcile conservation, economic development, and social inclusion (Domingues et al., 2020; Wang et al., 2023).

Practices such as sustainable pasture intensification, integrated crop-livestock-forestry systems (ICLFS), and agroforestry systems stand out as effective solutions to enhance carbon sequestration and reduce emissions. Intensification includes strategies such as fertilization, soil acidity correction, grazing management, and proper vegetation control. The cultivation of perennial species, such as oil palm, also contributes to the recovery of degraded areas, stabilization of biogeochemical cycles, and increased soil carbon retention (Wang et al., 2021; Rakesh et al., 2020).

These approaches combine environmental benefits with economic gains for local communities, representing key pillars in the transition to sustainable productive practices (Condé et al., 2020). Table 5 presents a summary of sustainable solutions and the main challenges for their adoption, as discussed throughout this section.

Perennial crops play a strategic role in this context. Açaí, for example, contributes to biodiversity conservation in riparian areas and offers sustainable economic alternatives. Oil palm, in turn, has been evaluated for its potential in integrated cultivation systems with other crops, thereby increasing carbon sequestration capacity. It can be grown on previously degraded lands, promoting land restoration, improving soil fertility, and enhancing organic matter storage (Rakesh et al., 2020; Gelaye & Getahun, 2024). These examples demonstrate how sustainable management practices can align environmental and economic objectives (Malhi et al., 2020; Weiskopf et al., 2020).

Despite recent progress, the large-scale adoption of these practices still faces significant challenges. Smallholders face economic constraints, such as limited access to credit and the absence of targeted incentives. Unregulated agricultural expansion, driven by crops like soybean and cattle ranching, continues to exert pressure on natural resources. Although pastures, oil palm, and soybean have potential for sustainable management, improper application may exacerbate environmental impacts (Amaral et al., 2019; Brito et al., 2021). Forest degradation also remains a major concern, with about 38% of the remaining Amazon areas affected by fires, logging, and extreme droughts, resulting in carbon emissions comparable to those from direct deforestation (Lapola et al., 2023).

Table 5
Sustainable solutions and main challenges for their implementation in the Amazon

Type of solution	Strategy or action	Main implementation challenges	Reference
Sustainable land use	ICLF, agroforestry systems, restoration of degraded pastures	Lack of technical assistance, limited credit access, weak public policies	Condé et al. (2020); Domingues et al. (2020); Wang et al. (2021)
Perennial crops	Açaí and oil palm in degraded areas for carbon sequestration and ecological restoration	Risk of monocultures, inappropriate land use, lack of integrated planning	Rakesh et al. (2020); Malhi et al. (2020); Gelaye & Getahun (2024)
Management technologies	No-tillage, BNF, animal waste management	Low adoption among smallholders; lack of government incentives	Piao et al. (2021); Quintão et al. (2021)
Reforestation and restoration	Reforestation with native species, restoration of ecological functions	Long return periods, high costs, absence of long-term policies	Flores et al. (2020); Deng et al. (2020)
Governance and social inclusion	Involvement of local communities and traditional peoples in sustainable management	Lack of legal recognition, exclusion of traditional knowledge from public policy	Domingues et al. (2020); Wang et al. (2023)
Environmental monitoring	Remote sensing, satellite imagery, artificial intelligence	Technological limitations, restricted data access, need for local technical capacity	Gatti et al. (2021)
Controlled agricultural expansion	Incentives for sustainable management of pastures, oil palm, and soy	Productivity pressure, improper land conversion, worsening environmental impacts	Amaral et al. (2019); Brito et al. (2021)
Forest degradation prevention	Measures against fires, illegal logging, and extreme droughts	Large extent of degraded areas; challenges in enforcement and mitigation	Lapola et al. (2023)

Notes: ICLF - integrated crop-livestock-forestry systems; BNF - biological nitrogen fixation.

Environmental governance is essential to address these challenges. Local communities and traditional peoples play a central role in preserving Amazonian ecosystems, offering practical knowledge on sustainable land management that enhances conservation and territorial governance. Integrating these actors into public policies is essential to align environmental preservation with social inclusion (Domingues et al., 2020; Wang et al., 2023). Furthermore, advanced technologies such as remote sensing, satellite monitoring systems, artificial intelligence, and high-resolution imagery are critical for detecting deforestation hotspots and planning forest regeneration (Gatti et al., 2021).

Finally, the restoration of degraded areas through reforestation with native species and the sustainable management of pastures is essential to restore ecological functions and mitigate climate change impacts. Investments in farmer training, economic incentives, and the integration of innovative technologies are key to the success of these strategies (Flores et al., 2020; Deng et al., 2020).

Although promising advances have been achieved, preserving the Amazon as a global environmental asset requires continuous effort and collaboration among governments, research institutions, local communities, and the private sector. With effective governance, integrated policies, and the strengthening of sustainable practices, it is possible to ensure a future where environmental conservation, economic productivity, and social inclusion advance together (Domingues et al., 2020; Malhi et al., 2020).

7. Conclusions

The Brazilian Amazon faces critical challenges due to climate change and environmental degradation, highlighting the importance of sustainable practices such as pasture management, agroforestry systems, and ICLF systems. This review showed that native forests maintain the highest soil C and N stocks. However, well-managed pastures with proper fertilization and forage intercropping also exhibit high accumulation potential, especially in deeper soil layers. In contrast, intensively managed agricultural soils tend to show greater losses of organic matter and increased GHG emissions, with particularly high N_2O fluxes observed in intensively grazed pastures under high fertilizer doses and elevated temperatures. The interaction between land use, fertilization, and microenvironmental conditions has been identified as a key factor in modulating CO_2, CH_4, and N_2O fluxes, reinforcing the need for adaptive strategies to mitigate environmental impacts. In this context, it is essential that scientific advances on soil C and N stocks and GHG fluxes inform public policies aimed at sustainable intensification and at valuing the Amazon as a strategic environmental asset.

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