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From policy to practice: the role of integrated systems in mitigating climate change in Brazil

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Abstract. Climate change, caused by human activities, hasimpacted global ecosystems, forcing countries to adopt mitigation and adaptation strategies. In this review, we explore the historical evolution of climate policies, focusing on international agreements such as the Kyoto Protocol and the Paris Agreement, and their implications for Brazil's agricultural sector. Brazilian agriculture, while contributing substantially to global food security, faces two major challenges: mitigating greenhouse gas emissions and adapting to climate-related vulnerabilities. Integrated crop-livestock-forestry systems emerge as a sustainable solution, balancing productivity with environmental responsibility. These systems not only help store carbon and improve soil health but also promote biodiversity and provide economic stability through a variety of outputs. By combining agronomy, environmental science, and policy, this review emphasizes how crucial integrated systems are to advancing sustainable farming practices in Brazil as we face climate changechallenges.
Keywords: agriculture,beef cattle, carbon,regenerative agriculture,sustainability.

Contextualization and analysis

Climate change: historical background

The greenhouse effect is a natural phenomenon that enables life on Earth, as GHGs, such as carbon dioxide (CO_2), methane (CH^4), nitrous oxide (N_2O), and chlorofluorocarbons (CFC), can absorb solar radiation, preventing the complete return of heat to space and retaining it in the atmosphere. The amount of retained heat contributes to the energy balance, preventing significant temperature variations (IPCC, 2022a). After the Industrial Revolution (late 1700s, early 1800s), the burning of fossil fuels for industrial energy generation resulted in a significant increase in GHG emissions, leading to the accumulation of these gases in the atmosphere, enhancing the greenhouse effect, and causing significant climate changes.

From the 1960s onward, environmental discussions began to grow due to problems caused by industrialization. Negative impacts such as pollution, traffic congestion, and noise pollution began to affect a significant portion of the population in developed countries. In this context, the book "Limits to Growth," led by the Club of Rome, was published, bringing considerable attention, and influencing public opinion (Meadows et al., 1972). In this book, authors addressed critical issues related to uncontrolled population growth, warning about the finite limits of natural resources and the potential consequences for the planet. The central discussion in the book was based on the need to balance economic development with environmental preservation, emphasizing that more sustainable measures would be necessary to make a viable future for humanity possible.

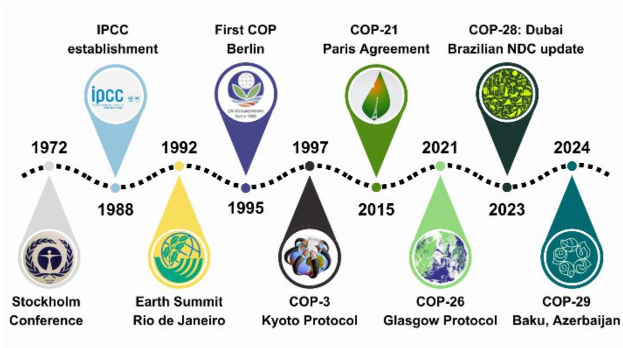
As several countries were discussing the need to take action regarding environmental preservation and society's concerns about the effects of pollution on life quality, the first meeting organized by the United Nations (UN) addressing global environmental issues was held in Stockholm, Sweden, in 1972 (Figure 1). The Stockholm Conference marked the entry of environmental issues into the global agenda with the participation of 113 countries, including Brazil, and over 400 governmental and non-governmental organizations (United Nations, 1973). During the conference, the United Nations Environment Program (UNEP) was established, and there was encouragement for the creation of national bodies dedicated to environmental issues. In Brazil, for example, the Special Secretariat for the Environment (SEMA) was established after the Stockholm Conference. The conference highlighted two opposing positions: developed countries advocating preservationists and developing countries asserting the need to use natural resources to promote economic development. Developing countries did not agree with goals to reduce industrial activities, arguing that such measures could compromise their economies. However, no agreements or targets were defined during this conference.

Some years after the Stockholm Conference in 1988, the UN established the Intergovernmental Panel on Climate Change (IPCC), an institution that remains prominent today as a scientific reference for research, analysis, and measurements regarding global climate (IPCC, 2023b). Four years later, in 1992, the largest event organized by the UN up to that point, known as ECO-92 or Earth Summit, took placein Rio de Janeiro, Brazil, involving more than 170 countries (United Nations, 1993). This meeting was responsible for the creation of the United Nations Framework Convention on Climate Change (UNFCCC), with the primary goal of addressing global climate change issues, and the Conference of the Parties (COP), which is an assembly of all member countries (or "Parties") signatory to the Convention, convening to implement public policies for the mitigation and adaptation to climate change.

In 1995, the first COP was held in Berlin, Germany, marking the initiation of negotiations to establish specific targets and deadlines for reducing GHG emissions by developed countries (UNFCC, 1995). In 1997, during COP-3 in Kyoto, Japan, the first international agreement aiming to reduce GHG emissions by 5.2% (based on 1990 levels) from 2008 to 2012 was signed, known as Kyoto Protocol (UNFCC, 1998). For the Kyoto Protocol to come into effect, it was necessary that at least 55 countries, responsible for at least 55% of global emissions, signthe agreement. Under this protocol, targets varied among countries, with more stringent goals for the 37 largest emitters, while developing countries such as Brazil, Mexico, Argentina, and India initially had no assigned reduction targets. The protocol only became effective in 2004 when Russia joined the agreement.

In 2012, the Kyoto Protocol expired, initiating discussions on the commitments that would succeed this agreement. In 2015, during COP-21 in Paris, France, the successor to the Kyoto Protocol, known as the Paris Agreement, garnered the participation of 195 signatories (UNFCC, 2016). The primary objective of the ParisAgreement was to curb global warming, keeping it below 2°C compared to pre-industrial levels, with additional efforts to limit the temperature increase to 1.5°C. In this context, Nationally Determined Contributions (NDCs) were established, playing a crucial role in the success of the Paris Agreement by obliging countries to take clear responsibilities regarding their emissions. Every five years, countries are obligated to review their NDCs, setting more ambitious and rigorous goals. In its first NDC, Brazil proposed a 37% reduction in greenhouse gas emissions by 2025, with an indicative target of 43% by 2030, both compared to 2005 levels (MCTIC, 2017). In 2021, during COP-26 in Glasgow, Scotland, the Glasgow Pact was signed, implying enhancedpractical efforts to limit global warming to 1.5°C. That year, Brazil updated its NDC and committed to the Glasgow Leaders' Declaration on Forests and Land Use, as well as the Global Methane Pledge. This includes the commitment to end deforestation by 2030 and a new target of a 50% reduction in greenhouse gas emissions by 2030 (Brazil, 2022). In 2023, Brazil announced an additional update to the NDC, aiming for a 48% reduction in emissions by 2025 and 53% by 2030 compared to 2005 levels (Brazil, 2023). These commitments underscore Brazil's dedication to addressing the challenges of climate change and contributing to environmental preservation.

Figure 1. Timeline of United Nations Conferences.

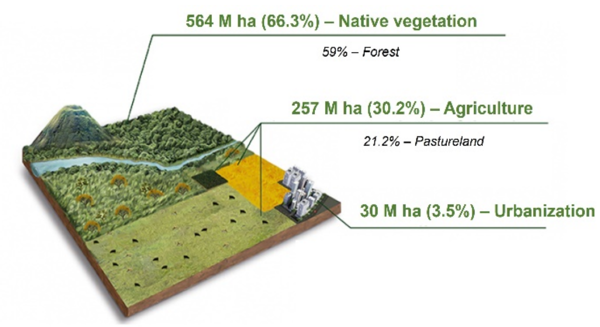


The role of Brazilian agriculture in adapting to and mitigating climate change

The evolution of Brazil's national environmental policy began in the 1970s, driven by social movements and external pressures. A significant turning point occurred in 1988 when thenotably The New York Times published an article titled "Vast Amazon Fires, Man Made, linked to Global Warming," and the editorial "Who is burning the Amazon?". These publications resonated globally, thrusting Brazil into the center of the debate on climate change and environmental preservation. Despite contributing only 2.4% of global GHG emissions and lacking an emission history comparable to developed countries (Crippa et al., 2023), Brazil is responsible for safeguarding the world's largest tropical forest, with 59% of the territory being forest (FAO, 2020).

Brazil's environmental responsibility is significantly rooted in the agricultural and land-use sectors, which together account for over half of the country's greenhouse gas emissions (SEEG, 2023). It is pertinent to emphasize that in Brazil, 30% of its area is dedicated to agriculture, including 21% allocated to pastures and around 8% for cropproduction (Figure 2). These numbers reflect a territorial distribution aiming to balance agricultural needs with environmental preservation. The challenge persists, however, especially due to the pressure for agricultural expansion and illegal deforestation, which directly impacts GHG emissions and biodiversity.

Figure 2. Brazil's land use. Adapted from: Embrapa Territorial (2020) and ABAG (2020)



Worldwide, agriculture and land use are responsible for 22% of global emissions, with livestock, a significant component of agriculture, accounting for 5.8% of global GHG emissions (IPCC, 2022b). In Brazil, the agricultural sector contributes 25% of the total GHG emissions, withlivestock accounting for 5% of the total (SEEG, 2023). The contribution is more significant for Brazil, given that the country holds the second-largest world cattle herd (FAOSTAT, 2023).

Despite the agricultural sector's greater contribution to GHG emissions in Brazil, the country assumes a relevant position in the global food production scenario. Brazilian agriculture contributed to 25% of the gross domestic product (CNA and CEPEA, 2023) and employed 27% of the economically active population (CEPEA and CNA, 2023) in 2022, and was responsible for 49% of exports in 2023 (Brazil, 2024a). On the global scenario, Brazil occupies the position of second-largest beef producer in the world (FAO, 2022), largest soybean producer, and third largest corn producer (FAOSTAT, 2023), and also leads the production and export of sugar, coffee, and orange juice (Brazil, 2024b), demonstrating a remarkable capacity to meet the global demand for food. Brazil's concern with climate change is evident, especially regarding the agricultural sector, as due to its characteristics and climate sensitivity, this sector becomes particularly vulnerable to climate change.

Beef cattle production in Brazil has a notable advantage since more than 80% of cattle are raised on pasture (ABIEC, 2023). This farming system is advantageous because ruminants have the unique ability to transform a source of protein of low biological value (fibers, forages), into a protein of high biological value (meat) (Mottet et al., 2017). Raising cattle on pasture also plays a fundamental role in reducing competition for land use between food production for humans and food production for animals (feed-food competition) (Dumont et al., 2020). A study indicated that changing 12% of global livestock production from monogastric to ruminant production could lead to a 5% reduction in GHG emissions, attributed to changesin land use and decreased demand for agricultural areas needed to feed ruminants (Cheng et al., 2022).

Despite some technological advances, livestock farming still faces challenges related to the use of degraded pastures and GHG emissions. According to LAPIG (2022), 55% of pastures in Brazil are degraded or in some stage of degradation, one of the main causes being inadequate management (establishment failure, high stocking rates that exceed pasture capacity, lack of fertilization, etc.) (Dias-Filho, 2014). Inadequate pasture management not only compromises the system productivity but also has a direct impact on forage production (Delevatti et al., 2019), soil quality, and soil C stocks (Maia et al., 2009), reducing the potential to deliver ecosystem services from grasslands. The reduction in forage production directly impacts animal intake (Trindade et al., 2016), affecting livestock production. By recovering degraded areas, land use efficiency can be increased (Damian et al., 2023), without opening new areas (i.e., deforestation), increasing soil C stocks (Braz et al., 2013),and contributing to GHG mitigation.

After COP-15, held in Copenhagen, Denmark, in 2009, where the Brazilian targets for reducing GHG emissions were updated, the ABC Plan was created, which demonstratesthe serious commitment of Brazilian agriculture to reduce GHG emissions (Brazil, 2012). The ABC plan is short for a Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low-Carbon Emission Economy in Agriculture, Livestock, and Forestry, and was conceived as a strategy to face the environmental challenges associated with agricultural activity. The ABC Plan goals are multifaceted, and address encouraging the adoption of sustainable agricultural practices, promoting efficiency in the use of natural resources, and the search for solutions to reduce GHG emissions. Among the main objectives of the plan are the intensification of agricultural production with low emissions, the recovery of degraded areas, the promotion of the sustainable use of natural resources, and the adoption of crop-livestock-forestry integrated systems.

In 2020, the ABC plan was renamed the Sector Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture, with a view to Sustainable Development and intending to expand the goals listed in the ABC plan (Brazil, 2022). Therefore, the search for more sustainable techniques, such as agricultural intensification and crop-livestock-forestry systems,has become a priority to reconcile production with sustainability.

Integrated systems

Integrated systems (i.e., livestock-forestry, crop-livestock, and crop-livestock-forestry) constitute an approach whose fundamental principle lies in the search for sustainable production. This concept proposes the integration of agricultural, livestock, and forestry activities in the same area, whether through intercropping, rotation, or succession, aiming to maximize productive, economic, and social aspects (Balbino et al., 2011).

The adoptionof integrated systems has increased due to the potential to enhance natural resource use efficiency (i.e., soil and water), reducing the dependence on external inputs (Szymczak et al., 2020), offsetting GHG, resulting from greater C sequestration capacity (Monteiro et al., 2024), greater nutrient cycling (Zago et al., 2020), and increase ecosystem services (Jose, 2009). When combining crop and livestock in the same farm operation,the sensitivity to fluctuations in commodity prices is lowered, illustrating its ability to reduce risks associated with price volatility (Reis et al., 2023).

By incorporating forages, such as *Brachiaria,* into the systems, soil health is improved. It is a result of the high soil organic matter input, which results in better soil structure (Salton et al., 2014), especially due to the extensive root system of *Brachiaria* (Baptistella et al., 2020). Integrating livestock, crops, and trees, not only promotes the conservation of natural resources, but in an environmental aspect, the presence of trees provides shade for livestock and can reduce heat stress and improve animal welfare (Domiciano et al., 2018; Magalhães et al., 2020; Romanello et al., 2023). Furthermore, trees play an important role in capturing C (Pezzopane et al., 2021), promoting biodiversity (Udawatta et al., 2019), and contributing to GHGmitigation (Monteiro et al., 2024).

Optimizing land use in integrated systems represents a strategic approach that stands out for diversified production in a farm (soybean, corn, meat, etc.), reducing the need to opennew areas (i.e., deforestation). Integrated systems can also improveforage productivity and nutritive value (Carvalho et al., 2019; Domiciano et al., 2020; Silva et al., 2020), resulting in higher livestock productivity, which directly impacts the system's profitability. Additionally, the planned harvest andcommercialization of wood products from these areas adds economic value to the system (Behling et al. 2021). Socially, the implementation of integrated systems contributes to the creation of more resilient environments, encouraging sustainable agricultural practices and promoting the diversification of income sources for farmers (Gil et al., 2015).

The inclusion of trees in integrated systems usually raises concerns about the possible negative impacts on forage production and crop components, due to the reduction in photosynthetically active radiation (Gomes et al., 2020a). Some studies already demonstrated that soybeans are more tolerant to shading compared to corn (Magalhães et al., 2019). Other studies state that, depending on the level of shade, forage production is not compromised (Gomes et al., 2020b; Nascimento et al., 2021) and can even result in increases in protein concentration (Lima et al., 2019). It is fundamental, however, to deepen the understanding of how forage in integrated systems is effectively used by ruminants at the rumen level, given that such dynamics can have direct effects on beef production and GHG emissions. As forage is the main feed source for ruminants and considering that the majority of enteric CH_4 emissions in agriculture derive from ruminal fermentation (IPCC, 2023a), it is essential to investigate ruminal fermentation parameters on forages in integrated systems. This knowledge is essential for assessing whether the inclusion of forage in integrated systems not only sustains productivity but also helps reduceCH_4 emissions, supporting sustainability and environmental mitigation goals.

Assessing the characteristicsof each system is crucial toincentivizethe adoption of integrated systems in Brazil. The vast territorial extension, with different biomes, results in a wide range of arrangements and strategies that can be adopted as integrated systems. Each system will need to accommodate its attributes,with specific soils, weather, and the adapted forages, crops, and trees. Furthermore, the diversity of Brazilian regional markets and logistics, influenced by the vast agricultural landscape, shapes the specific components of each system to meet local demands and opportunities.Thus, understanding the uniqueness of each system is essential to guide effective and sustainable management strategies in different regions of Brazil.

The carbon market opportunities also need to be considered. Thus, the analysis of the carbon balance of integrated systems contributes to understanding the environmental impact and market opportunities while designing sustainable practices. The carbon balance refers to the difference between C emissions and the C sequestration of a system. It contributes to understanding the GHG emissions offset and the participation of these producersin the carbon market. Practices that result in a negative balance, that is, in net carbon absorption, can generate tradable carbon credits. Monteiro et al. (2024) analyzed the C balance of four systems: livestock in monoculture, crop-livestock, livestock-forestry, and crop-livestock-forestry. All systems presented a negative C balance when expressed as kg CO_2eq/kg carcass or kg CO_2eq/kg edible protein. Among the systems, livestock-forestry showed the greatest net C balance, with values of -20 kg CO_2eq/kg carcass and 70 kg CO_2eq/kg edible protein.These credits represent a valuable commodity in the carbon market, where companies seek to offset their emissions by purchasing credits from projects that promote net carbon reduction.

In Brazil, the voluntary carbon market was recently approved by Congress and is currently waiting for regulation. While the agricultural sector will not be includedin the regulatory framework, it still has the potential to contribute by generating carbon credits. Therefore, by assessing the C balance in the systems, producersare not only promoting environmental sustainability but also opening doors for active participation in the carbon market, supporting global efforts and public policies towards climate change.

Despite that, some points must be considered, as the consolidation of the carbon market can face several challenges, such as the high cost associated with the development of carbon projects, which can limit access for small rural producers who often lack financial and structural resources; the lack of adequate technical training to conduct analyses and quantify carbon on farms; and the shortage of reliable and standardized data for C accounting, which compromises the accuracy of estimates and the credibility of the generated credits. This estimation also needs to consider the complex nature of agricultural systems, where multiple factors, such as soil type, farming practices, weather, and crop species, directly influence carbon stocks and flows.

To overcome these challenges is necessary investments in research, development of accessible technologies, and educationprograms for producers and consultants. Only with an integrated approach, supported by research and education programs, will be possible to ensure that the carbon market becomes an effective and inclusive tool for promoting sustainability in the agricultural sector.

Final considerations

It is evident that Brazilian agriculture plays a crucial role in adapting and mitigating the impacts of climate change. The country's extensive area, which includes livestock, agriculture, and forestry production, presents challenges and opportunities. Based on that, integrated systems, such as crop-livestock-forestry, will be the driver tomaximize natural resource efficiency, offset GHG emissions, and enhance soil health while also mitigating climate change by sequestering carbon.

Furthermore, the analysis of carbon balance is essential, as it demonstrates the potential to absorb carbon, which can be translated into carbon credits. This is particularly relevant in the context of Brazil’s evolving carbon market, where opportunitiesto generate carbon credits and attract international investments are increasing.

As Brazil updates its NDCs and commits to reducing emissions, its agricultural sector must continue to innovate and adopt more sustainable practices, especially when facing climate change challenges. The adoption of integrated systems plays a crucial role in achieving these goals, enabling agricultural production and environmental preservation to coexist while supporting the growing global population.

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