CARBON FARMING: POTENTIAL FOR MITIGATING CLIMATE CHANGE IN BRAZILIAN AGRICULTURAL SOILS

CARBON FARMING: POTENCIAL DE MITIGAÇÃO DAS MUDANÇAS CLIMÁTICAS EM SOLOS AGRÍCOLAS BRASILEIROS

CARBON FARMING: POTENCIAL DE MITIGACIÓN DEL CAMBIO CLIMÁTICO EN LOS SUELOS AGRÍCOLAS BRASILEÑOS

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ABSTRACT

One of the greatest contemporary socio-environmental challenges, climate change poses risks to food security and the resilience of tropical agroecosystems. In this context, the set of soil management practices known as carbon farming represents a smart strategy for maximizing carbon sequestration and reducing net greenhouse gas emissions from agricultural activities. This study evaluated the effectiveness of these practices in Brazil through a Systematic Literature Review (SLR), based on the PRISMA protocol. Fifty-six articles published between 2015 and 2025 were analyzed, extracted from the SciELO, Web of Science, Scopus, and Google Scholar databases. The studies were organized into thematic areas, with emphasis on the frequency of publications for: no-till farming and crop rotation (25%), crop-livestock-forest integration (18%), pasture recovery (16%), and agroforestry/silvopastoral systems (14%). The results indicated consistent gains: SPD increased stocks by up to 1.5 Mg C ha^{-1} $year^{-1}$; cover crops reduced nitrogen fertilization by up to 30%; water management in irrigated rice mitigated up to 96% of CH_4 emissions; fertigation in sugarcane reduced N_2O by 50%; pasture recovery and silvopastoral systems added up to 1.2 Mg C ha^{-1} $year^{-1}$; ILPF increased up to 2.8 Mg C ha^{-1} $year^{-1}$; and SAFs/SPS achieved up to 7 Mg C ha^{-1} $year^{-1}$. It can be concluded that carbon farming constitutes a portfolio of effective and complementary practices, but its large-scale expansion depends on overcoming technical and economic barriers, in addition to strengthening public policies.

Keywords: Low-Carbon Agriculture. Carbon Sequestration. Greenhouse Gases.

RESUMO

Um dos maiores desafios socioambientais contemporâneos, as mudanças climáticas impõem riscos à segurança alimentar e à resiliência dos agroecossistemas tropicais. Nesse contexto, o conjunto de práticas de manejo do solo denominado carbon farming representa uma estratégia inteligente para maximizar o sequestro de carbono e reduzir as emissões

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líquidas de gases de efeito estufa provenientes das atividades agrícolas. Este estudo avaliou a efetividade dessas práticas no Brasil por meio de uma Revisão Bibliográfica Sistemática (RBS), fundamentada no protocolo PRISMA. Foram analisados 56 artigos publicados entre 2015 e 2025, extraídos das bases SciELO, Web of Science, Scopus e Google Scholar. Os trabalhos foram organizados em eixos temáticos, com destaque segundo a frequência de publicações para: sistema de plantio direto e rotação de culturas (25%), integração lavoura-pecuária-floresta (18%) e recuperação de pastagens (16%) e sistemas agroflorestais/silvipastoris (14%). Os resultados indicaram ganhos consistentes: o SPD aumentou estoques em até 1,5 Mg C ha^{-1} ano^{-1}; culturas de cobertura reduziram a adubação nitrogenada em até 30%; o manejo hídrico em arroz irrigado mitigou até 96% das emissões de CH_4; a fertirrigação em cana-de-açúcar reduziu em 50% o N_2O; a recuperação de pastagens e os sistemas silvipastoris adicionaram até 1,2 Mg C ha^{-1} ano^{-1}; a ILPF elevou até 2,8 Mg C ha^{-1} ano^{-1}; e SAFs/SPS alcançaram até 7 Mg C ha^{-1} ano^{-1}. Conclui-se que o carbon farming constitui um portfólio de práticas eficazes e complementares, mas sua expansão em larga escala depende da superação de barreiras técnicas e econômicas, além do fortalecimento de políticas públicas.

Palavras-chave: Agricultura de Baixo Carbono. Sequestro de Carbono. Gases de Efeito Estufa.

RESUMEN

El cambio climático, uno de los mayores retos socioambientales contemporáneos, supone un riesgo para la seguridad alimentaria y la resiliencia de los agroecosistemas tropicales. En este contexto, el conjunto de prácticas de gestión del suelo denominado «agricultura de carbono» representa una estrategia inteligente para maximizar la captura de carbono y reducir las emisiones netas de gases de efecto invernadero procedentes de las actividades agrícolas. Este estudio evaluó la eficacia de estas prácticas en Brasil mediante una revisión bibliográfica sistemática (RBS), basada en el protocolo PRISMA. Se analizaron 56 artículos publicados entre 2015 y 2025, extraídos de las bases SciELO, Web of Science, Scopus y Google Scholar. Los trabajos se organizaron en ejes temáticos, destacando según la frecuencia de publicaciones: sistema de siembra directa y rotación de cultivos (25 %), integración de cultivos, ganadería y bosques (18 %), recuperación de pastizales (16 %) y sistemas agroforestales/silvipastoriles (14 %). Los resultados indicaron ganancias consistentes: el SPD aumentó las reservas hasta en 1,5 Mg C ha^{-1} $año^{-1}$; los cultivos de cobertura redujeron la fertilización nitrogenada hasta en un 30 %; el manejo hídrico en el arroz de regadío mitigó hasta el 96 % de las emisiones de CH_4; la fertirrigación en la caña de azúcar redujo en un 50 % el N_2O; la recuperación de pastizales y los sistemas silvopastoriles añadieron hasta 1,2 Mg C ha^{-1} $año^{-1}$; el ILPF aumentó hasta 2,8 Mg C ha^{-1} $año^{-1}$; y los SAF/SPS alcanzaron hasta 7 Mg C ha^{-1} $año^{-1}$. Se concluye que el cultivo de carbono constituye una cartera de prácticas eficaces y complementarias, pero su expansión a gran escala depende de la superación de barreras técnicas y económicas, además del fortalecimiento de las políticas públicas.

Palabras clave: Agricultura Baja en Carbono. Secuestro de Carbono. Gases de Efecto Invernadero.

1 INTRODUCTION

Climate change is one of the greatest contemporary socio-environmental challenges, whose effects go beyond ecological and economic boundaries, imposing risks to food security, ecosystem services, and human well-being (Abreu et al., 2024). The intensification of the greenhouse effect, derived from the accumulation of gases of anthropogenic origin, has caused changes in water regimes, greater frequency of extreme events, and productive instability in several regions (Ferreira et al., 2022; Baião; Massi; Sousa Junior, 2024). The soil-water interface also responds to land use, with higher dissolved C fluxes in agricultural basins (Rosa et al., 2017). Changes in energy and moisture balance are already detectable in Amazonian urban areas (Santos et al., 2024). In this context, agriculture occupies a paradoxical role: it is a significant source of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), but it also has high potential to act as a carbon sink through sustainable management practices (Sousa et al., 2021; Oliveira et al., 2025).

CO_2, mainly from the burning of fossil fuels, deforestation and intensive land use, represents the largest share of global emissions. Predictive tools indicate higher CO_2 in soil disturbance scenarios (Vitória et al., 2022). CH_4, although less abundant, has a Global Warming Potential (GWP) 28 times higher than CO_2, with enteric fermentation and irrigated rice being its main sources (Guamán-Rivera et al., 2025). N_2O, related to nitrogen fertilization, has an average atmospheric life of 114 years and a GWP 265 times higher than CO_2, making tropical agriculture one of the largest responsible for its emission (Furtado Neto et al., 2019; Sousa et al., 2021).

Soil stands out as a strategic component in this process, as it constitutes the largest active terrestrial carbon reservoir, with estimated stocks between 1,500 and 2,400 Gt C, surpassing plant biomass (Gomide et al., 2024; Oliveira et al., 2025). Regional estimates confirm the variation of stocks according to use and management in Latosols of Southern Brazil (Magalhães et al., 2024). However, the country's history of land use, with extensive conversions of forests and savannas into pastures and monocultures, has resulted in significant edaphic carbon losses (Silva et al., 2024; Freitas et al., 2024). Recent studies also suggest that the warming of subsurface horizons accelerates the decomposition of recalcitrant compounds, threatening the long-term stability of stocks (Baião; Massi; Sousa Junior, 2024; Amelung et al., 2020). In contrast, secondary forest succession accumulates measurable carbon over time (Villanova et al., 2019).

In this scenario, the concept of carbon farming emerges, defined as the set of agricultural, livestock, and forestry practices aimed at maximizing carbon sequestration and net GHG reduction (Freitas et al., 2024). National empirical evidence highlights significant gains: the no-tillage system (NTS) increased carbon stock by up to 1.5 Mg ha^{-1} $year^{-1}$ and reduced erosion by five times (Carvalho et al., 2017; Ozório et al., 2024; Tanaka et al., 2025); cover crops reduced the need for nitrogen fertilization by up to 30% (Cordeiro et al., 2015); in irrigated rice, intermittent drainage reduced CH_4 emissions by up to 96% (Carvalho et al., 2021); in sugarcane fields, subsurface fertigation reduced N_2O emissions by 50% and raw harvesting resulted in a positive balance of up to 1,484 kg CO_2eq ha^{-1} $year^{-1}$ (Faquim et al., 2024).

In livestock, silvopastoral systems and the recovery of degraded pastures increased stocks by up to 1.2 Mg ha^{-1} $year^{-1}$ and reduced the intensity of enteric emissions (Silva et al., 2024a). Integrated crop-livestock-forest systems (ICLFS) have increased stocks by up to 2.8 Mg ha^{-1} per $year^{-1}$, in addition to reducing emissions per animal by 30% and increasing meat productivity by 40% (Tonini, 2023). Agroforestry and silvopastoral systems (AFS and SPS) showed sequestration rates of up to 7 Mg C ha^{-1} $year^{-1}$, reconciling climate mitigation with benefits to biodiversity and food security (Tonini, 2023; Guamán-Rivera et al., 2025).

Public policies are fundamental for the dissemination of these practices. The ABC Plan (2010–2020) exceeded targets by serving 54 million hectares, with a mitigation of 193.67 Mt CO_2eq, while the ABC+ (2020–2030) foresees expansion to 72.68 million hectares by 2030, including NTS, ICLFS, SAFs, and pasture recovery (Tonini, 2023; Abreu et al., 2024). At the international level, initiatives such as RECSOIL/FAO reinforce the recarbonization of soils as a central axis of climate mitigation and adaptation (Guamán-Rivera et al., 2025). In view of this, understanding the potential of carbon farming in Brazil implies integrating scientific evidence, productive benefits, institutional barriers, and alignment with national and international policies. The consolidation of these practices represents a strategic opportunity to increase agroecosystem resilience, value ecosystem services, and position the country as a protagonist in the global climate agenda.

Thus, the objective of this work was to carry out a comprehensive evaluation of the effectiveness and adoption of carbon farming practices in Brazilian agricultural soils, focusing on multiple aspects. The research sought, first, to investigate the effectiveness of these practices in carbon sequestration and in the mitigation of net emissions of CO_2, CH_4 and N_2O, evaluating, in parallel, the agronomic, environmental and socioeconomic co-benefits. To this end, the study unfolded in the evaluation of conservation practices, such as no-tillage, crop rotation, cover crops, and the use of biochar, regarding their impact on carbon. It also examined water and nutritional management strategies in crops such as irrigated rice and sugarcane, specifically aiming at reducing CO_2, CH_4 and N_2O fluxes. The research included the analysis of sustainable livestock, covering the recovery of degraded pastures, ecological intensification and silvopastoral systems, with a focus on the mitigation of enteric methane and the increase of productivity. Finally, it investigated the potential of integrated systems such as Integrated Crop-Livestock-Forest (ICLFS) and agroforestry systems (SAFs/SPS), highlighting their contribution to carbon sequestration, productive diversification and the generation of socio-environmental co-benefits, in addition to identifying the technical, economic and institutional barriers that prevent the widespread adoption of these practices.

2 METHODOLOGY

This study was developed through a Systematic Literature Review (RBS), based on the guidelines of Kitchenham and Charters (2007) and on the PRISMA protocol, adapted to Agricultural and Environmental Sciences. The adoption of this approach in reviews on greenhouse gases and agriculture is already consolidated in the field (Galdino; Signor, 2024). In addition, the selection of analytical axes considered operational definitions established in national technical documents, such as those referring to ICLFS (Cordeiro et al., 2015).

The bibliographic search covered the period from 2015 to 2025, without excluding previous studies considered fundamental to the theme. The SciELO, Web of Science, Scopus and Google Scholar databases were consulted, using descriptors in Portuguese and English, both separately and in combination, depending on the database, such as: carbon farming, carbon farming, mitigation, greenhouse gas emissions, soil carbon, irrigated rice, sugarcane, pastures, ICLFS, SAFs, SPS and Brazil.

In the first screening, the descriptors were applied separately to broaden the scope of the search. Then, the results were refined based on inclusion criteria:

1- Empirical studies conducted in Brazilian agricultural soils or in analogous edaphoclimatic conditions;
2- Presentation of quantitative results on soil carbon stocks, CO_2, CH_4 and N_2O fluxes or mitigation metrics in agricultural, livestock and forestry systems;
3- Publications in indexed journals or technical papers with DOI.

Review studies without empirical data, purely theoretical modeling, reports without methodological transparency, and studies whose main focus was "soil quality" unrelated to carbon mitigation or sequestration were excluded.

The selected articles were systematized in the following main axes:

I. Conservation agricultural practices:

- NTS and crop rotation
- cover crops

- Biochar

II. Integrated systems:

- ICLFS
- SAFs and SPS

III. Management:

- Hydr: irrigated rice
- Nutritional (N): sugarcane

IV. Sustainable livestock:

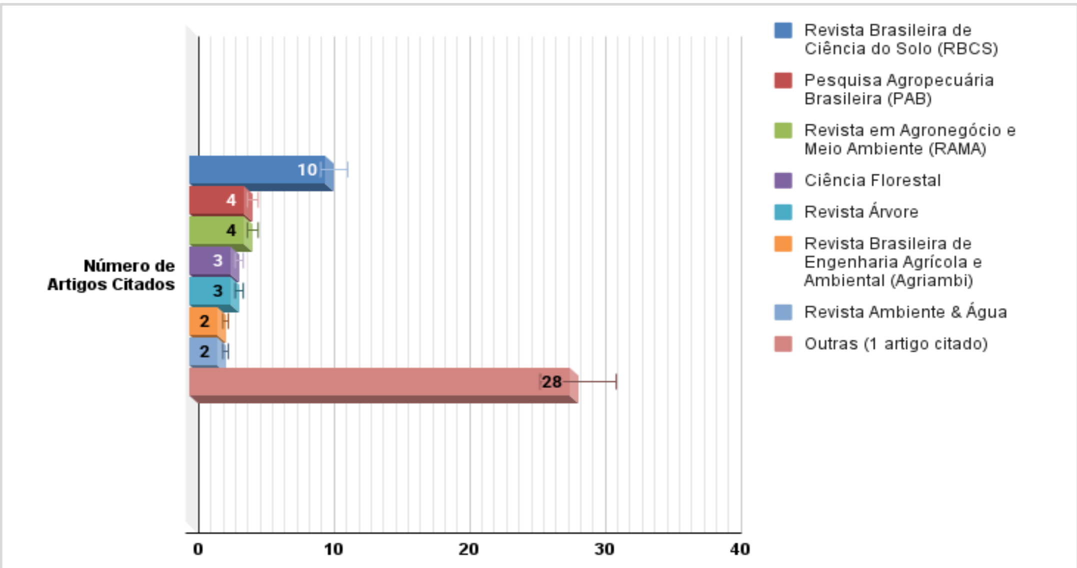
- pasture recovery, ecological intensification and enteric methane mitigation.

The extraction of data included the location of the studies, soil type, climate, methodology used, numerical results (stocks, flows and reductions), limitations and links with public policies. The analysis combined descriptive synthesis (mean values and ranges) and critical interpretation, considering the consolidated literature and institutional reports. This approach ensured the reproducibility of the methodological path and ensured a focus on carbon farming practices applicable to the Brazilian context.

At the end of the screening, 56 scientific articles were identified. In terms of editorial standards, the analysis revealed a majority concentration of articles in reference journals in the area of Agrarian and Environmental Sciences classified in the highest strata of Qualis CAPES (Figure 1), with the Brazilian Journal of Soil Science being the most frequent for publications on the subject.

Figure 1

Number of publications per journal identified in the review



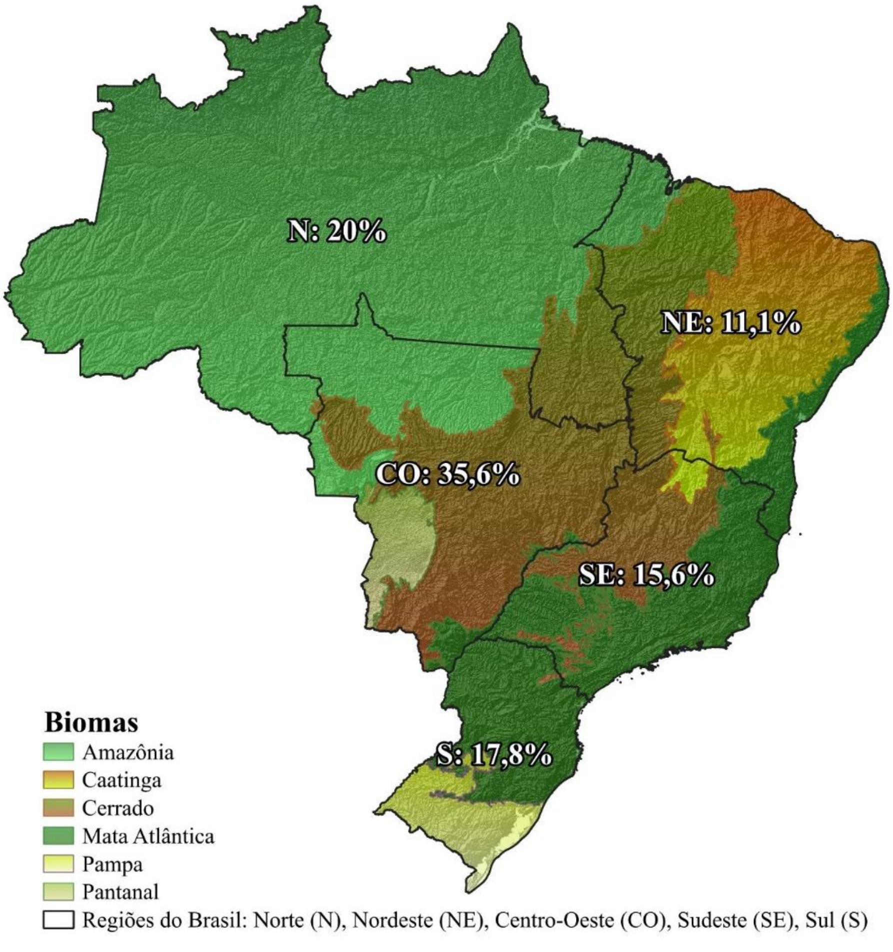
Source: Prepared by the authors themselves.

In addition to the analysis of the journals and their classifications, the distribution of the papers among the different regions of Brazil allowed us to identify in which edaphoclimatic and productive contexts carbon farming has been most investigated (Figure 2). Most of the studies focus on representative areas of the Cerrado and Amazon biomes, followed by relevant records in the South and Southeast, evidencing both the strategic importance of the Cerrado for large-scale agricultural production and the vulnerability of the Amazon in land use scenarios. Other biomes, such as the Caatinga and Pampa, had fewer investigations, which indicates research gaps and the need to expand the geographic coverage of studies on carbon farming in Brazil.

Thus, the results presented below discuss in detail the thematic and regional distribution of the identified practices, as well as their gains, co-benefits and limitations, composing a critical overview of the contribution of carbon farming to the mitigation of climate change in the country.

Figure 2

Regional distribution of the literature review



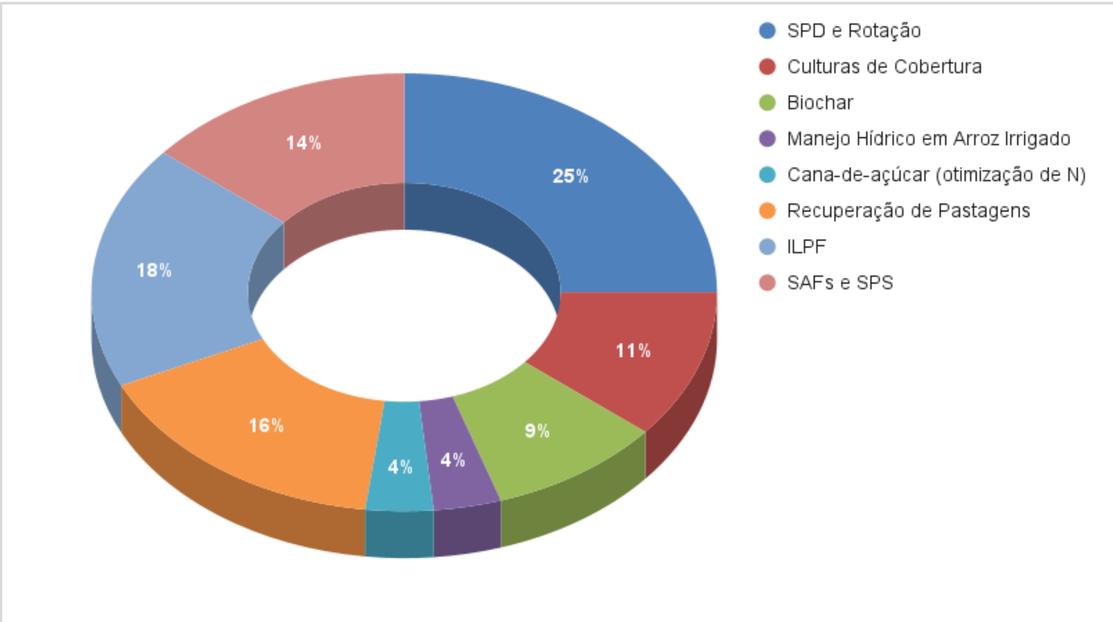
Source: Prepared by the authors themselves.

3 RESULTS AND DISCUSSIONS

The analysis revealed the conservation practices axis as the most investigated, totaling 45%, with NT and crop rotation being the main target of the studies (Figure 3). Next, the integrated ICLF systems, SAFs and SPS, represented 32% of the studies developed. The sustainable livestock axis also stood out, with the recovery of pastures reaching 16% and representing the third most researched practice. Together, it is possible to verify the prominence of these carbon farming strategies in the national mitigation agenda linked to land use and cover.

Figure 3

Distribution of the bibliographic collection by thematic axes of carbon farming



Source: Prepared by the authors themselves.

Within each axis, the most recurrent practices were identified (Table 1). In cover crops, grasses such as black oats and brachiaria and legumes such as mucuna and sunn hemp stand out (Table 1), associated with nutrient cycling and biological nitrogen fixation. As for NT and rotation, studies on erosion reduction and greater water infiltration predominate, while others emphasize gains in stable organic matter. In the biochar axis, most of the articles evaluated agro-industrial residues (sugarcane, gliricidia, chicken litter), with evidence of increased pH, CEC and long-term carbon sequestration.

In irrigated rice, all studies compared continuous flooding to intermittent drainage, recording significant reductions in CH_4, although accompanied by N_2O peaks under aerobic conditions. In sugarcane, the studies analyzed subsurface fertigation and raw harvest, both pointing to N_2O mitigation and positive carbon balance. Corrective fertilization practices, introduction of forages and silvopastoral systems, all associated with increases in carbon stocks and reduction of enteric emissions, are predominant in pasture recovery. The ICLF axis focused on studies on soil attributes, such as fertility, aggregation, and carbon stocks, as well as gains in animal productivity. Finally, in SAFs and SPS, the introduction of forage and nitrogen-fixing trees, soil carbon sequestration, and long-term economic feasibility analysis stand out.

Table 1

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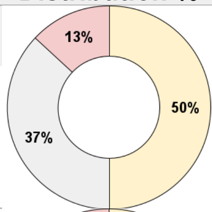
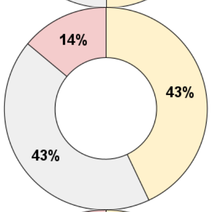
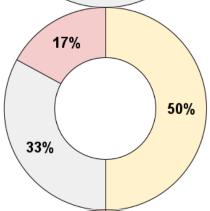
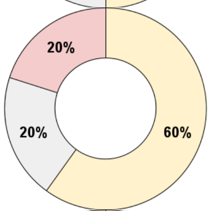
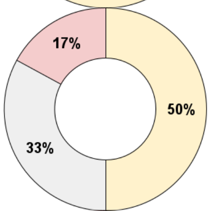
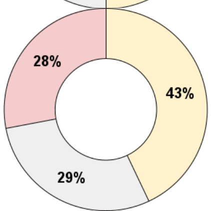
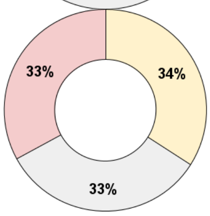
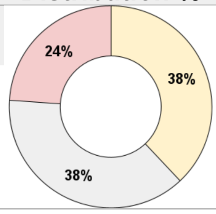
Thematic Axis		Distribution %
SPD and Rotation	Grain-cotton/corn-soybean-brachiaria rotation Associated toppings (oats, velvet bean, etc.)	
Cover Crops	Legumes (velvet bean, sunn hemp, vetch, jack beans) Mixtures (grasses + legumes)	
Biochar	Biochar + organic inputs (compost, poultry litter) Biochar in Oxisols (fertility/microbial biomass)	
Water Management in Irrigated Rice	Waste management Irrigation + synchronized fertilization	
Sugar cane (N optimization)	Raw harvest with straw Biochar in sugarcane fields	
Pasture Recovery	Conversion to integrated systems Wooded pastures / sheep-olive cultivation integration	
ICLFS	Grain-livestock-forest integration Ecosystem services / aggregate stability	

Thematic Axis		Distribution %
SAFs and SPS	SAFs with native species / indigenous communities	
	SPS in the Pampa and Amazon	
	Soil / biodiversity indicators	

Source: Prepared by the authors themselves.

These results demonstrate that, although the literature is distributed among different strategies, there is consensus regarding the strategic role of conservation practices (NTS, covers, biochar) and integrated systems (ICLFS, SAFs and SPS, pasture recovery) as pillars of carbon farming in Brazil.

The analysis of the articles showed that conservation practices, such as NTS, cover crops, and biochar use, showed consistent results in terms of increasing carbon stocks and improving soil quality, even though they face limitations associated with input costs, water availability, and the absence of consolidated incentive mechanisms. On the other hand, water management practices in irrigated rice and nitrogen optimization in sugarcane have shown great efficiency in mitigating methane (CH_4) and nitrous oxide (N_2O) fluxes, but require careful technical adjustments to avoid adverse effects, such as N_2O emission peaks.

Integrated systems, including pasture recovery, ICLFS, SAFs, and SPS, were the ones that demonstrated the greatest robustness in terms of multiple benefits. In addition to sequestering carbon at rates higher than other practices, research points to increased productivity, promotion of income stability, and reduction of climate risks, reinforcing the centrality of these systems in low-carbon agriculture policies. However, the complexity of management, the need for specialized technical assistance and high initial costs remain relevant barriers to integrated expansion. Thus, the comparison shows that no practice is exempt from limitations, reinforcing the need for combined strategies to enhance gains and mitigate risks. Carbon farming, in this sense, should be understood as a portfolio of complementary solutions, in which the balance between technical efficiency, economic viability, and public policies is decisive for its large-scale adoption.

Table 2 summarizes the empirical results of the review and gathers guidelines for the formulation of practical recommendations for farmers, managers, and policymakers aimed at mitigating climate change in Brazil. The comparative analysis of practices demonstrates that there is no single solution, but a set of strategies that stand out for the magnitude of the gains and the consistency of the results. Among them, SAFs and SPS stand out for their high carbon sequestration potential, with average values of up to 7 Mg C ha^{-1} $year^{-1}$, in addition to the partial neutralization of enteric methane and the generation of multiple ecosystem services (Table 2).

On a more immediate scale, ICLF systems and pasture recovery also have high performance, reconciling greenhouse gas mitigation, increased animal productivity, and economic diversification. Water management in irrigated rice, in turn, appears as a practice of high climate efficiency, achieving reductions of up to 96% in CH_4 emissions, without compromising productivity. Biochar, on the other hand, although with significant results in modeling and field experiments, still depends on overcoming technical and logistical barriers for gains in scale (Table 2).

Regarding the economic and financial focus, only a restricted portion of the evaluated studies explicitly addressed the long-term feasibility or the relationship with carbon markets. Studies such as Lefebvre et al. (2020) and Torres et al. (2024) have highlighted the potential of biochar and SAFs to generate carbon credits or positive financial return after the consolidation of the system. Similarly, Castro et al. (2018) and Petter et al. (2019) related the application of biochar to increased agricultural productivity, suggesting indirect gains in profitability. Embrapa's technical report (2021) and institutional analyses reinforce the importance of instruments such as the ABC+ Plan and payment mechanisms for environmental services, although the empirical literature still has significant gaps in cost quantification and economic return in tropical conditions.

Table 2

Carbon farming practices in Brazil: carbon sequestration gains, emission reduction, co-benefits and challenges

Prática	Principais Ganhos	Co-benefícios	Desafios
SPD e Rotação	Acréscimos de até 0,6–1,5 Mg C ha^{-1} ano^{-1}; redução de erosão em até 80%; aumento da infiltração em 30–40% (Ozório *et al*., 2024; Tanaka *et al*., 2025)	Maior eficiência no uso de nutrientes; aumento da estabilidade produtiva; adaptação a extremos climáticos (Freitas *et al*., 2024)	Limitação hídrica em regiões semiáridas; mecanização adaptada; custos de capacitação técnica (Abreu *et al*., 2024)
Culturas de Cobertura	Redução de 25–30% da adubação N mineral; incremento de até 0,32 g C kg^{-1} no carbono microbiano; liberação de 37 kg N ha^{-1} (Sousa *et al*., 2021; Freitas *et al*., 2024)	Proteção contra erosão (até 4,1 Mg ha^{-1} ano^{-1} de solo preservado); redução de até 40% da exportação de P; melhora da qualidade da água (Tanaka *et al*., 2025; Ozório *et al*., 2024)	Custos de sementes; competição por área; ausência de mecanismos consolidados de PSA (Tonini, 2023)
Biochar	Aumento de 2,35 ± 0,4 t C ha^{-1} ano^{-1} em estoques de solo; redução de até 60% das emissões acumuladas de N_2O; elevação da CTC em 25% (Andrade *et al*., 2015; Petter *et al*., 2019; Tito *et al*., 2025)	Melhoria da fertilidade do solo; aumento da produtividade de culturas; integração com cadeias agroindustriais (Silva *et al*., 2024b)	Alto custo de pirólise; ausência de normativas técnicas; logística de transporte e aplicação (Assad *et al*., 2022)
Manejo Hídrico em Arroz Irrigado	Redução de até 96% das emissões de CH_4; produtividade mantida em 9,8–10,3 t ha^{-1}; risco de picos de N_2O até 98 g N_2O-N ha^{-1} dia^{-1} (Zschornack *et al*., 2016; Lopes *et al*., 2018)	Redução de até 30% no consumo de água; custo-benefício positivo (Zschornack *et al*., 2016)	Necessidade de sincronizar irrigação e fertilização; risco de aumento de N_2O em períodos aeróbios (Sousa *et al*., 2021)
Cana-de-Açúcar (Otimização do N)	Emissões de N_2O reduzidas em até 50%; fatores de emissão caíram de 4,26% para 1,69%; saldo positivo de 1.484 kg CO_2eq ha^{-1} ano^{-1} (Lopes *et al*., 2018; Tavares *et al*., 2018)	Maior atividade microbiana; integração com bioenergia; substituição de combustíveis fósseis (Silva *et al*., 2024b)	Alto custo inicial da fertirrigação; baixa difusão em pequenas propriedades (Abreu *et al*., 2024; Embrapa, 2021)
Recuperação de Pastagens	Incremento de até 1,2 Mg C ha^{-1} ano^{-1} em estoques; redução de 20–30% nas emissões entéricas (Ribeiro *et al*., 2023; Tonini, 2023)	Aumento de até 35% na produtividade animal; melhoria da qualidade da carne; redução da pressão por desmatamento (Silva *et al*., 2024a; Signor *et al*., 2022)	Custos de recuperação elevados; baixa assistência técnica rural (Abreu *et al*., 2024)
ILPF	Sequestro de até 2,8 Mg C ha^{-1} ano^{-1}; aumento de 40% na produtividade da carne; redução de 30% nas emissões entéricas (Freitas *et al*., 2024; Alcântara *et al*., 2024; Tonini, 2023)	Diversificação de renda; redução do risco de incêndios em até 40%; inclusão socioambiental (Abreu *et al*., 2024)	Exige assistência técnica especializada; custos iniciais elevados; complexidade de manejo (Embrapa, 2021)
SAFs e SPS	Sequestro médio de até 7 Mg C ha^{-1} ano^{-1}; neutralização parcial do CH_4 entérico; aumento de biodiversidade (Torres *et al*., 2017; Tonini, 2023; Guamán-Rivera *et al*., 2025)	Redução de até 40% nos custos com adubação; viabilidade econômica a partir do 10º ano; diversificação de renda (Baldotto & Baldotto, 2018; Torres *et al*., 2024)	Altos custos iniciais; horizontes de retorno longos; necessidade de PSA e certificações (Assad *et al*., 2022)

Source: Adapted from Ozório et al. (2024); Tanaka et al. (2025); Freitas et al. (2024); Sousa et al. (2021); Zschornack et al. (2016); Lopes et al. (2018); Tavares et al. (2018); Ribeiro et al. (2023); Alcântara et al. (2024); Torres et al. (2017); Tonini (2023); Guamán-Rivera et al. (2025); Baldotto & Baldotto (2018); Abreu et al. (2024); Silva et al. (2024a, 2024b); Embrapa (2021).

3.1 NO-TILLAGE SYSTEM (NTS) AND CROP ROTATION

NTS has consolidated itself as the main conservationist technology in Brazilian agribusiness, based on three basic principles: no soil disturbance, permanent maintenance of vegetation cover and diversification of species through rotation. These elements act in an integrated manner to reduce the mineralization of organic matter, control erosion, and expand stable organic carbon stocks (Ozório et al., 2024; Tanaka et al., 2025). Evidence indicates that, under tropical conditions, NT significantly reduced soil losses and increased water infiltration in Oxisols, with gains close to 30–40% compared to conventional tillage (Tanaka et al., 2025). Trials under natural rain show lower soil loss with vegetation cover in NT (Salomão et al., 2020).

Regarding carbon dynamics, experiments conducted in the Cerrado revealed increases of up to 0.6 Mg C ha^{-1} $year^{-1}$ in the first years of NT adoption (Ozório et al., 2024). These increments were mainly associated with the stabilization of the humified fraction of organic matter, located in subsurface horizons. Tanaka et al. (2025) reinforce that the diversification of species in rotation favors the formation of macroaggregates, essential for the physical protection of carbon. In ICL, improvements in soil physical and chemical attributes reinforce carbon protection (Beutler et al., 2016). In sugarcane cultivation, conservation systems such as raw harvesting and subsurface fertigation reduced N_2O emissions by more than 40% compared to conventional management, resulting in a positive carbon balance in the system (Faquim et al., 2024).

Despite the benefits, the full adoption of the SPD faces important barriers. In semi-arid regions - mainly in the Caatinga biome, but also in areas of the Cerrado and Atlantic Forest - water limitation compromises the production of straw, a crucial element for the practice (Silva et al., 2024). In addition, adapted mechanization costs, lack of technical training, and cultural resistance hinder its large-scale dissemination (Freitas et al., 2024). In this scenario, public policies play a decisive role. The ABC Plan (2010–2020) promoted the adoption of NTS in millions of hectares, resulting in significant CO_2eq mitigation, and the current phase, ABC+ (2020–2030), provides for the expansion of the area cultivated with conservation practices to 72 million hectares by 2030 (Abreu et al., 2024; Tonini, 2023).

NTS also contributes to the efficiency of nutrient use and the climate resilience of agricultural systems. Studies show that conservation systems have higher nitrogen retention in the soil and lower N_2O fluxes, indicating gains in nitrogen fertilization efficiency (Sousa et al., 2021). Diversification by integrated systems increases resilience to extremes (Assad et al., 2022), studies show that the reduction in bulk density and the increase in infiltration favor adaptation to events of intense rain and droughts, frequent in the Cerrado (Silva et al., 2024).

From a socioeconomic point of view, properties that adopted integrated systems and NTS recorded productivity gains and greater income stability (Freitas et al., 2024). The inclusion of NTS in Payment for Environmental Services (PES) programs and in green rural credit lines reinforces its centrality as a key technology of low-emission agriculture in Brazil.

3.2 COVER CROPS

Cover crops play a strategic role in carbon farming, as they insert diversified biomass into the system, improve nutrient cycling, and protect the soil against bad weather. Sacramento et al. (2018) highlight the variability of such effects according to soil class, especially in Regolitic Neosoils. Grasses such as black oats and brachiaria are widely used for their high C/N ratio, which favors carbon stabilization, while legumes such as mucuna, sunn hemp, and vetch offer nitrogen by biological fixation, reducing dependence on mineral fertilizers (Freitas et al., 2024; Sousa et al., 2021; Ozório et al., 2024). In experiments with Ultisols, Acosta et al. (2014) observed rapid decomposition and greater release of N to vetch, while black oats promoted longer-lasting immobilization and carbon protection. Isotopic approaches have quantified the incorporation of biomass into SOM (Severo et al., 2017).

In irrigated rice environments, the effects of cover crops are contrasting. Zschornack et al. (2016) found that ryegrass and ryegrass + dogwood biomass increased cumulative CH_4 emissions to values between 118 and 119 kg ha^{-1} per harvest, equivalent to 6,691 kg CO_2eq ha^{-1}, of which 98% were attributed to methane. However, the adoption of intermittent drainage reduced these flows by up to 96%, without compromising productivity, which remained between 9.8 and 10.3 t ha^{-1}. These results reinforce the importance of planning the use of cover crops in conjunction with water management, in order to avoid climate trade-offs (Carvalho et al., 2021; Sousa et al., 2021).

On the economic level, the practice faces barriers associated with the cost of seeds, competition for area, and the absence of consolidated mechanisms for remuneration for the environmental services provided (Abreu et al., 2024; Tonini, 2023). Public policies have sought to overcome these limitations: the ABC+ Plan recognizes cover crops as a priority technology for mitigation, while international programs, such as RECSOIL/FAO, already link the practice to Payment for Environmental Services (PES) mechanisms and carbon credits (Tonini, 2023; Abreu et al., 2024). The combination of institutional incentives and agronomic gains reinforces the potential of these crops to expand carbon sequestration in Brazilian agricultural soils (Freitas et al., 2024; Ozório et al., 2024).

Rotation with brachiaria raised microbial C in the Cerrado (Savioli et al., 2024), additional evidence strengthens this diagnosis. In Cerrado Latosols, Savioli et al. (2024)

showed that the use of brachiaria in rotation increased microbial carbon by 20% compared to uncovered areas, indicating greater soil biological activity (Freitas et al., 2024; Silva et al., 2024). Ferreira (2016) demonstrated that legumes such as jack beans and mucuna can reduce the need for mineral nitrogen fertilization by up to 35%, generating direct savings for the producer (Sousa et al., 2021). From an environmental point of view, the maintenance of permanent cover reduced soil loss in hillside areas by five times and decreased phosphorus exports to water bodies by 40%, contributing to water quality (Ozório et al., 2024; Tanaka et al., 2025). These results, which can be seen in Table 3, support the integration of cover crops into PES and carbon credit policies, expanding their adoption especially in small and medium-sized properties.

Table 3

Cover crop species and observed results

Species	Main effect	Numerical results
Avena strigosa	High C/N ratio, promotes nutrient immobilization and protects MOS	Reduction of 4.1 Mg ha^{-1} $year^{-1}$ of soil loss in NT **(Tanaka *et al.*, 2025)**
Urochloa spp.	Deep roots, increases aggregate stability and microbial C	↑ 0.32 g C kg^{-1} soil in microbial C in Oxisols **(Freitas *et al.*, 2024)**
Mucuna pruriens	Biological N fixation, reduces mineral fertilizer	↓ 12 kg N ha^{-1} of mineral fertilization (≈ 25–30%) **(Sousa *et al.*, 2021)**
Crotalaria juncea	High biomass production, nutrient recycling	Production of 8.4 Mg ha^{-1} of biomass; increase in SOM **(Freitas *et al.*, 2024)**
Vicia sativa	Fast decomposition, accelerated release of N	Release of 37 kg N ha^{-1} in Ultisols **(Sousa *et al.*, 2021)**
Lolium multiflorum	High biomass in winter; Dense coverage	↑ emissions of 118–119 kg CH_4 ha^{-1} $crop^{-1}$ in irrigated rice **(Zschornack *et al.*, 2016)**
Lotus corniculatus	Legume; FBN; improves straw C/N ratio	In mixture with ryegrass: 6,691 kg CO_2eq ha^{-1} $harvest^{-1}$ **(Zschornack *et al.*, 2016)**

Source: Adapted from Tanaka et al. (2025); Freitas et al. (2024); Sousa et al. (2021); Zschornack et al. (2016).

3.3 BIOCHAR AS A SEQUESTRATION STRATEGY AND ECONOMIC VIABILITY

Biochar, produced by pyrolysis of biomass under low oxygen availability, has been studied as a long-term carbon sequestration strategy due to its high chemical recalcitrance and potential to improve soil attributes. Modeling conducted by Lefebvre et al. (2020) demonstrated that the application of biochar derived from sugarcane residues, at a dose of 4.2 t ha^{-1} $year^{-1}$, could promote average increases of 2.35 ± 0.4 t C ha^{-1} $year^{-1}$ in soil carbon stocks. On a regional scale, the adoption of this practice throughout the sugarcane area of the State of São Paulo would have the potential to mitigate approximately 50 Mt CO_2e per year, equivalent to 31% of the state's emissions in 2016.

From an agronomic point of view, experiments carried out in low fertility planosols by Castro et al. (2018) found that the application of 15 t ha^{-1} of Gliricidia sepium biochar raised soil pH, increased phosphorus and potassium availability, and favored snap bean yield when associated with organic fertilization and microbial inoculation. In eucalyptus plantations, biochar modulated soil CO_2 and chemical attributes (Silva et al., 2024a). The biochar-compost combination increased corn fertility and yield (Tito et al., 2025). These results reinforce the ability of biochar to act as a conditioner of low-fertility tropical soils, increasing the resilience of agricultural systems (Petter et al., 2019).

Despite the potential identified, the diffusion of biochar on a large scale in Brazil still faces challenges related to the cost of installing pyrolysis units, the logistics of transport and application, and the absence of specific regulations regarding quality parameters (pH, fixed carbon content, and contaminants). These factors limit its full inclusion in public policies for agricultural mitigation. Even so, field results and economic modeling suggest that biochar can integrate low-carbon strategies in the agro-industrial sector, especially in regions with intensive sugarcane cultivation.

3.4 WATER MANAGEMENT IN IRRIGATED RICE CULTIVATION

Irrigated rice, predominant in southern Brazil, is recognized as one of the most methane-emitting agricultural crops (CH_4), due to the continuous water depth that favors anaerobic conditions. Tests conducted in Rio Grande do Sul have shown that areas under permanent flooding have significantly higher CH_4 emissions compared to systems managed with fallow. The inclusion of winter crop residues has further intensified CH_4 fluxes, highlighting the need to integrate agricultural practices with water management to mitigate such emissions (Zschornack et al., 2016A). Converging results have been observed in national trials with waste management and drainage (Zschornack et al., 2016B).

Intermittent drainage, characterized by planned cycles of flooding and lowering of the water depth, has been shown to be the most efficient alternative to mitigate emissions in this system. Results indicated significant reductions in CH_4 fluxes, without compromising average grain yield (Zschornack et al., 2016A). However, this practice intensified the emission of nitrous oxide (N_2O) in aerobic periods, especially in areas fertilized with legumes, reinforcing the need to synchronize irrigation and nitrogen fertilization to reduce N_2O fluxes (Lopes et al., 2018).

From a political-institutional point of view, water management in irrigated rice has already been incorporated into the portfolio of the ABC+ Plan, being considered a priority mitigation strategy and linked to specific credit lines. On a global scale, FAO recommends the adoption of Alternate Wetting and Drying (AWD) as a technique capable of substantially reducing CH_4 emissions in rice paddies, positioning Brazil as a potential protagonist in the implementation of sustainable technologies in one of the most methane-intensive crops.

Recent research reinforces that water management, when associated with the rational use of fertilizers, can further enhance mitigation. Lopes et al. (2018) highlighted that the combination of intermittent drainage and installment fertilization significantly reduced net GHG emissions, maintaining regional productivity. In addition to the environmental benefits, the technique has economic gains: producers reported significant reductions in water consumption, a fundamental aspect in regions with growing water scarcity. In this way, intermittent drainage is consolidated as a practice of high climate efficiency and positive cost-benefit, capable of repositioning Brazilian rice farming in the low carbon agenda.

3.5 SUGARCANE AND NITROGEN OPTIMIZATION

Sugarcane is considered one of the most strategic crops for Brazil, both for its relevance in the energy matrix and for its participation in the international bioenergy market. However, nitrogen fertilization applied to the crop is responsible for significant emissions of nitrous oxide (N_2O), a greenhouse gas with global warming potential about 298 times higher than CO_2 (IPCC, 2006). On average, studies in Brazilian sugarcane fields indicate annual flows between 2.0 and 6.0 kg N_2O-N ha^{-1} $year^{-1}$, equivalent to 600–1,800 kg CO_2eq ha^{-1} $year^{-1}$, depending on management (Sousa et al., 2021; Lopes et al., 2018). These values place sugarcane at the center of discussions on GHG mitigation in the agricultural and energy sectors.

Fertigation practices have been shown to be highly effective in reducing these emissions. Lopes et al. (2018) found that subsurface drip application reduced accumulated N_2O emissions by up to 50% compared to surface fertilization, with emission factors (EF) falling from 4.26% to 1.69%. In addition, Tavares et al. (2018) demonstrated that the raw harvest, with the maintenance of straw in the field, resulted in a positive balance of 1,484 kg CO_2eq ha^{-1} $year^{-1}$, associated with greater microbial activity and the reuse of organic matter. Recent results confirm lower N_2O with drip and raw harvesting (Faquim et al., 2024). Studies indicate that water reuse strategies alter soil C and N stocks in the short term, efficient irrigated systems reduce the carbon footprint per unit of product (Carmo et al., 2016; Corrêa et al., 2021).

From the point of view of public policies, sugarcane was incorporated as a priority crop in the ABC+ Plan, linked to practices such as efficient fertigation and harvesting without burning, supported by specific credit lines from RenovAgro (Abreu et al., 2024). This integration is strategic: it is estimated that the adoption of these technologies in 8 million hectares of sugarcane fields by 2030 can reduce more than 12 Mt CO_2eq (Abreu et al., 2024; Embrapa, 2021). In addition to the environmental benefits, such measures can strengthen the competitiveness of the sugar-energy sector in international bioenergy and carbon credit markets.

Complementary studies reinforce the role of sugarcane in the low-carbon agenda. In tropical conditions in the Northeast, Tavares et al. (2018) observed that the simultaneous adoption of raw harvesting, efficient fertigation, and straw maintenance reduced net emissions by up to 1.6 t CO_2eq ha^{-1} $year^{-1}$, transforming the crop into a potential net carbon sink. Recent results also indicate that the application of biochar in sugarcane fields can reduce N_2O emission factors to approximately 1% of the applied N, a value lower than the standard estimates of the IPCC (2006), in addition to increasing the cation exchange capacity of the soil (Andrade et al., 2015; Petter et al., 2019). The integration of sugarcane with the energy sector expands the synergy between mitigation of agricultural emissions and decarbonization of the electricity matrix, since the use of straw and bagasse as bioenergy replaces fossil fuels (Silva et al., 2024B). These results show that sugarcane should be treated as a priority axis in national mitigation programs and in global carbon markets.

3.6 SUSTAINABLE LIVESTOCK AND PASTURE RECOVERY

Brazilian livestock accounts for approximately 60% of GHG emissions from the agricultural sector, with enteric methane being the main source (Guamán-Rivera et al., 2025). In extensive systems in the Amazon, the carbon footprint can reach 16.2 kg CO_2eq/kg of live weight, reaching values up to four times higher in subsistence systems (Guamán-Rivera et al., 2025). These indicators highlight the urgency of adopting mitigating practices, especially in degraded pasture areas, which have lower carbon stocks than those observed in preserved forest areas (Silva et al., 2024A). Riparian fragments maintain higher C stocks and structure than those of open areas (Soares et al., 2023).

Strategies for the recovery of degraded pastures associated with practices such as corrective fertilization and the introduction of adapted forage species show great potential for reversing this scenario. Freitas et al. (2024) demonstrated that the conversion of degraded pastures into integrated systems in the Cerrado promoted a significant increase in soil carbon stocks. Similarly, Ribeiro et al. (2023) found greater carbon lability and stability in conservation management areas when compared to conventional pastures. Silvopastoral systems (SPS) also stand out: Tonini (2023) reported mitigation of enteric emissions and productive gains in the Pampa biome, while Guamán-Rivera et al. (2025) observed that the presence of trees contributes to animal thermal comfort and reduction of emissions intensity per kilogram of meat. Integrated systems with fruit and sheep also have a great additional potential for mitigation (Silva et al., 2024C).

Public policies reinforce the centrality of the theme in the national climate agenda. The ABC+ Plan established the goal of recovering 15 million hectares of pastures by 2030, with a mitigation potential of 83 Mt CO_2eq (Embrapa, 2021). Programs such as "Carbon Neutral Meat", developed by Embrapa, and Payment for Environmental Services (PES) initiatives have created certification and remuneration mechanisms that encourage the adoption of low-carbon systems. In this way, sustainable livestock farming not only contributes to climate mitigation, but also strengthens Brazil's image as a global supplier of animal protein with environmental differentiation.

From a socioeconomic point of view, the sustainable intensification of livestock generates relevant impacts. Silva et al. (2024A) showed that well-managed pastures have higher soil fertility and better nutrient availability, which is reflected in animal productivity gains. In a complementary way, Signor et al. (2022) showed that animal production systems in the semi-arid region can be adjusted to reduce net GHG emissions, highlighting the importance of integrating soil and forage management into mitigation. In addition to the environmental benefits, the recovery of pastures represents greater income generation and reduced pressure for the opening of new areas, contributing to contain deforestation.

3.7 INTEGRATED CROP-LIVESTOCK-FOREST (ICLF)

Crop-Livestock-Forest Integration (ICLFS) is considered one of the most complete practices in the low-carbon portfolio, as it combines productive, environmental, and social gains in the same technological arrangement. The system promotes synergies between plant and animal components, increasing agroecosystem resilience in different Brazilian biomes. In areas of the Cerrado, Freitas et al. (2024) demonstrated that the conversion of degraded pastures into integrated systems promoted an increase in soil carbon stocks and improved fertility. In a complementary way, Alcântara et al. (2024) found that areas of natural regeneration and integration systems showed greater aggregate stability and greater protection of organic matter, confirming the role of ICLFS in the recovery of soil quality.

From an economic point of view, ICLFS offer income diversification by integrating annual crops, livestock, and forest production, reducing risks associated with market variations. Experiences conducted in southern Brazil show significant gains: Tonini (2023) showed that silvopastoral systems linked to ICLFS showed an increase in animal productivity and mitigation of enteric emissions compared to conventional systems. In addition, analyses by Ribeiro et al. (2023) reinforce that areas under integrated systems have higher carbon stocks and greater soil chemical stability compared to monocultures, consolidating ICLFS as a robust model of effective mitigation.

The ABC+ Plan established the goal of expanding the adoption of ICLFS to 10 million hectares by 2030, with specific credit lines made available by RenovAgro (Embrapa, 2021). At the same time, training and technical assistance programs have been strengthened, since the complexity of management requires specialized knowledge in plant science, animal husbandry and forestry. In this context, ICLFS should be understood not only as an agricultural technology, but as a territorial governance system, capable of reconciling climate mitigation, adaptation, and food security on a regional scale.

In addition to the direct mitigation of greenhouse gases, ICLFS promote high-value ecosystem services. In Cerrado areas, Tanaka et al. (2025) observed that integrated systems increased aggregate stability and improved the potential for water infiltration into the soil, factors that favor resilience in the face of prolonged droughts. Another relevant aspect is the contribution of ICLFS to the reduction of fires: Abreu et al. (2024) highlighted that the diversification of agricultural systems reduces vulnerability to fire, due to greater soil cover and maintenance of microclimatic moisture. In soils of medium fertility, integration increased fertility, C stock, and aggregate stability (Beutler et al., 2016; Silva et al., 2021). From a socioeconomic point of view, Ozório et al. (2024) pointed out that the adoption of diversified systems contributes to greater productive stability, reinforcing the potential of ICLFS as a socio-environmental inclusion policy. These results show that the practice transcends the agricultural scope, configuring itself as a strategy for sustainable rural development on a large scale.

3.8 AGROFORESTRY (SAFS) AND SILVOPASTORAL SYSTEMS (SPS)

AFS and SPS integrate trees, crops, and animals into spatially planned arrangements, increasing the functional complexity and resilience of agroecosystems. These systems have been recognized as low-carbon alternatives, with the potential to neutralize emissions and expand carbon stocks in different Brazilian biomes. Tonini (2023) demonstrated that the introduction of trees in pastures in the Pampa biome neutralized the net enteric methane balance, resulting in a positive carbon balance in woody biomass and soil. In the Amazon, Guamán-Rivera et al. (2025) found that SPS systems reduced the intensity of emissions per kilogram of meat and improved the thermal comfort of the animals, reducing risks in extreme heat events.

Recent evidence reinforces the strategic role of SAFs and SPS. Tonini (2023) confirmed that silvopastoral systems in the Pampa contribute to neutralizing enteric emissions, while Guamán-Rivera et al. (2025) demonstrated that such systems can reduce the intensity of GHG emissions in tropical livestock. From an environmental point of view, Ozório et al. (2024) highlighted that integrated systems increase organic matter and the stability of soil aggregates, favoring carbon sequestration. Analyses by Baldotto & Baldotto (2018) show that the adoption of agroforestry arrangements can improve soil quality indicators and ensure greater long-term sustainability.

The associated co-benefits are multiple and relevant. In addition to mitigating greenhouse gases, SAFs and SPS promote increased biodiversity, soil conservation, and improved animal diet. Forage tree species, such as Gliricidia sepium and Tithonia diversifolia, have been associated with increased herd feed efficiency and reduced nutrient losses (Freitas et al., 2024; Ozório et al., 2024). Comparatively, well-structured AFS can accumulate carbon stocks significantly higher than conventional monocultures (Torres et al., 2017). These results reinforce the potential of agroforestry practices to consolidate Brazil as an international reference in low-carbon agriculture and livestock.

From a political-institutional point of view, the adoption of SAFs and SPS still faces barriers, such as high initial costs and longer return horizons, however, studies also indicate that SAFs can achieve a positive internal rate of return after the tenth year, reinforcing their economic viability (Torres et al., 2024). The ABC+ Plan established the goal of expanding these systems to 4 million hectares by 2030, offering credit lines (Embrapa, 2021). In addition, the inclusion of SAFs and SPS in Payment for Environmental Services (PES) policies and in carbon certifications, such as the "Carbon Neutral Meat" program, is considered essential to make their dissemination economically viable.

4 CONCLUSION

Carbon farming is a robust, cost-effective and technically feasible strategy for mitigating climate change in Brazil, whose effectiveness depends on stable institutional management arrangements. The systematic analysis of the scientific literature, institutional reports and empirical evidence pointed to the consistent increase in soil carbon stocks and biomass, in the net reduction of CO_2, CH_4 and N_2O, in the structural and biological improvement of the soil and in associated productive gains achieved by the conservation practices evaluated: NTS, cover crops, biochar, water management in irrigated rice, fertigation in sugarcane, sustainable livestock, ICLFS, SAFs and SPS.

In the agronomic field, NT showed gains of up to 1.5 Mg C ha^{-1} year^{-1}, a five-fold reduction in erosion and a 30 to 40% increase in water infiltration compared to conventional tillage. Cover crops reduced the need for mineral nitrogen fertilization by 25 to 30%, associating biological fixation with biomass input. In irrigated rice, intermittent drainage reduced CH_4 emissions by up to 96%, although accompanied by N_2O peaks that require careful management of irrigation and fertilization. In sugarcane fields, subsurface fertigation reduced N_2O emissions by approximately 50%, while the raw harvest promoted a positive balance of 1,484 kg CO_2eq ha^{-1} year^{-1}.

In livestock, silvopastoral systems and the recovery of degraded pastures increased soil carbon stocks by up to 1.2 Mg C ha^{-1} year^{-1} and reduced the intensity of enteric emissions, in addition to generating co-benefits such as greater animal thermal comfort and reduced mortality in extreme heat events. ICLFS stood out for expanding carbon stocks by up to 2.8 Mg C ha^{-1} per year^{-1} and increasing meat productivity by 40% compared to conventional systems. On the other hand, the AFS and SPS showed average sequestration rates of up to 7 Mg C ha^{-1} year^{-1}, in addition to diversifying income and promoting high-value ecosystem services.

Despite the advances, challenges persist that limit the full expansion of carbon farming. Among them are the lack of calibrated emission factors for tropical soils, high implementation costs in integrated systems, climate monitoring deficits and insufficient technical assistance for family farmers. Overcoming these obstacles requires integrated policies that combine scientific innovation, financial incentives and qualified rural extension. The ABC Plan (2010–2020) served 54 million hectares and mitigated 193.7 Mt CO_2eq, and its continuity with ABC+ (2020–2030) projects expansion to 72.68 million hectares by 2030. On an international scale, initiatives such as RECSOIL/FAO reinforce the recarbonization of soils as a central axis of climate mitigation and adaptation. The sectoral integration with bioenergy also expands the mitigation portfolio.

It is concluded that carbon farming should be understood as a strategic pillar of low-carbon agriculture in Brazil. Its large-scale adoption has the potential to reduce GHG emissions, ensure the permanence of carbon stocks, promote productive resilience, and value ecosystem services. In this way, the country is able to take a leading role in the global climate agenda, consolidating agricultural soils as climate assets and strengthening the competitiveness of its sustainable agriculture.

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