

Perspective

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Perspectives on carbon footprint of agricultural land-use in Brazil

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Abstract

Brazil is one of the main producers in the agricultural and forestry sector worldwide, with production systems based on high consumption of inputs that contribute to high levels of greenhouse gas (GHG) emissions. This paper presents an analysis of the scenario of national GHG emissions and carbon footprints in the major production systems of agriculture, including livestock production and forestry, and the potential for soil carbon storage as a mitigation strategy under these systems. The main sources of national GHG emissions are beef cattle due to enteric fermentation and the management of agricultural soils through the use of nitrogen fertilizers. The increasing adoption of low-carbon agriculture has led to a reduction in the carbon footprint through no-till technologies, agrosilvopastoral systems, N₂ fixation, and tree plantations. These technologies deserve to be increasingly disseminated to generate economic opportunities leading to financial gains from the commercialization of carbon credits and payment for environmental services.



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Keywords: GHG emissions, low-carbon agriculture, land-use systems, sustainable intensification

INTRODUCTION

Agriculture is practiced throughout the national territory of Brazil, covering six different biomes (Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal, and Pampa) that present variations in climate, soil, vegetation, water regime, relief, and specific demands in the environmental, social, and economic sectors, in addition to presenting different types of agricultural production systems. This complexity represents a major challenge in terms of meeting the goals of food security, increased productivity, and sustainable production standards. Since the implementation of the green revolution in Brazil in the 1960s, the agricultural and forestry sectors have undergone major changes with the ultimate objective of obtaining the highest yields. The production process was intensified with the large-scale use of machinery and other inputs for maximizing the production of crops and commodities for the foreign market. Thus, monocultures and agro-industry were intensified as viable and very profitable economic activities.

This production model based on high consumption of inputs causes additional greenhouse gas (GHG) emissions that contribute to global climate change with soil degradation (compaction, erosion, and reductions of organic matter levels and soil fertility) and reduced biodiversity, among other losses^[1]. Total gross GHG emissions reached 2.16 billion tons of CO₂ equivalent (GtCO₂eq) in Brazil in 2020. Land use changes were the most responsible for GHG emissions due to deforestation and burning of native vegetation for agricultural use, mining activities, and urban expansion. Other major sectors include agriculture, energy sector, industrial processes, and waste management^[1] [Figure 1]. Thus, most national emissions are directly or indirectly linked to agricultural production and land-use change. The present paper describes the national GHG emissions, the carbon footprints in some production systems, and the potential for soil carbon storage as a mitigation strategy in Brazil. The use of low-carbon agriculture and a reflection on the need for paradigm shifts towards sustainable development are also emphasized.

The agricultural sector

The strategic relevance of the agricultural sector for Brazil lies in the fact that it aggregates the various production chains of agriculture (crops and livestock) and tree plantations, which together constitute the country's agribusiness sector. This sector employed approximately 19 million people in 2021, including workers in both the countryside and companies linked to the agribusiness chain. Of this total, 11.5 million workers are linked to family farming, representing most of the jobs created in the countryside and the majority of Brazilian agricultural properties^[2]. This agribusiness model contributed 26.6% of the national gross domestic product (GDP) in 2020. The country's GDP totaled BRL (Brazilian Real, R\$) 7.45 trillion (R\$1 = approximately USD 0.20, early 2022), and the agricultural sector's GDP reached almost BRL 2 trillion (70% from the agricultural sector and 30% from livestock)^[2], while the forestry sector contributed around R\$100 billion^[3]. The performance of agricultural production was due to the high commodity prices in the international market, mainly grains, coffee (*Coffea arabica*), meat, and eucalyptus (*Eucalyptus* sp.). However, revenue growth was limited by rising production costs since most of the inputs (fertilizers, pesticides, herbicides, etc.) were imported. These, as well as the cost of fossil fuels (diesel and gasoline), are subject to the uncertainties of international market prices.

Brazil has been a major producer and exporter of several commodities including soybeans (*Glycine max*), maize (*Zea mays*), beans (*Phaseolus vulgaris*), sugarcane (*Saccharum officinarum*), coffee, cocoa (*Theobroma cacao*), and livestock for the past several decades^[4,5]. The estimated total grain production for the 2021/2022 harvest was 291.1 million tons from 72 million hectares (8.5% of the total area of the national territory). This

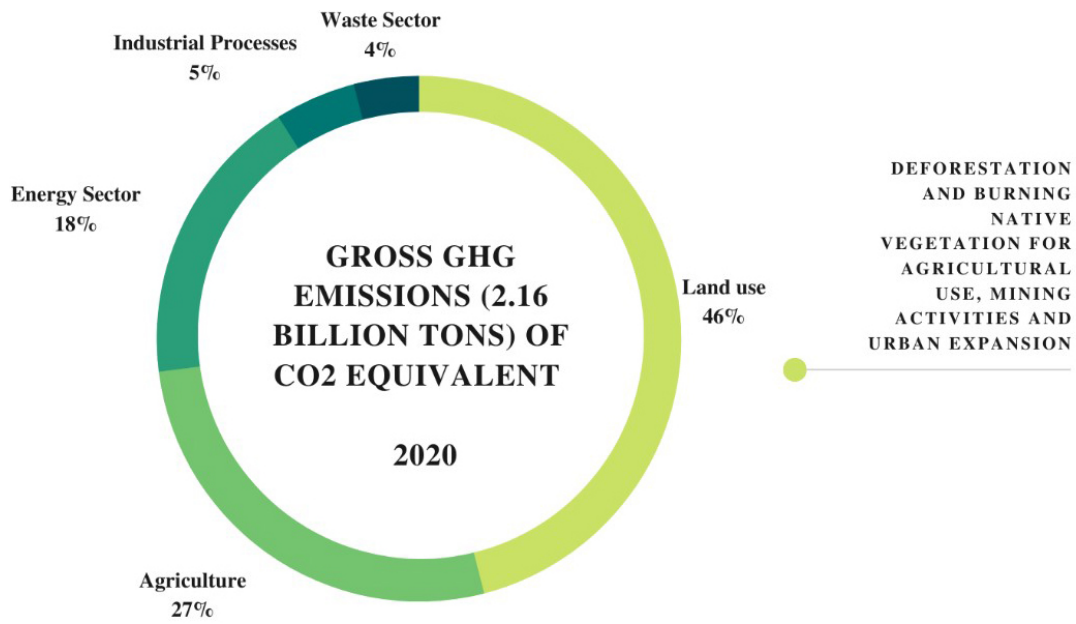


Figure 1. Total gross GHG emissions reached 2.16 billion tons of CO₂ equivalent (G_tCO_{2eq}) in Brazil in 2020.

corresponded to a 15% increase compared to the 2020/2021 harvest, with an 11% increase in productivity, for an increase of only 3.7% in planted area. Most of the total planted areas of grains are used for producing soybeans (56%) and maize (29.1%), with beans on about 4% of the area [Table 1]. The area under sugarcane for the 2021/2022 harvest corresponded to approximately 1% of the total area of the national territory with a production of 568.4 million tons, while the coffee plantation area was 0.2% and cocoa 0.07%, producing 47.7 million bags of coffee (1 bag = 60 kg of coffee) and 259,310 tons of dry cocoa beans [Table 1]. The size of the area occupied by the main vegetable crops in Brazil represents 2.5% of the area occupied by soybeans, producing 20.8% of the volume and 16.4% of the revenue. Tomatoes (*Solanum lycopersicum*), onions (*Allium cepa*), carrots (*Daucus carota*), potatoes (*Solanum tuberosum*), garlic (*Allium sativum*), sweet potatoes (*Ipomoea batatas*), melons (*Cucumis melo*), and watermelon (*Citrullus lanatus*) are the main vegetables grown in Brazil. Beef cattle herds totaled approximately 218.2 million head reared on 160 million hectares of pastures^[6].

The Brazilian forestry sector has been characterized as a major international player in the industrial tree plantation sector since 2000. Since then, it has been characterized by the expansion of planted areas and the consolidation of the sector's technological development. Forest products are the third largest in terms of national agribusiness exports value, below soybean and meat production. Tree plantations in Brazil totaled about 9 million hectares in 2020, of which 7.5 million hectares were planted with eucalyptus, 1.7 million hectares with pine, and 0.4 million with other species, including rubber (*Hevea brasiliensis*), acacia (*Acacia sp.*), teak (*Tectona grandis*), and paricá (*Schizolobium amazonicum*)^[3]. Consumption for industrial uses from tree plantations totaled 216.6 million m³ of wood in 2020, with eucalyptus plantations representing 75% of this total. The paper and cellulose sector stood out as the main consumer (41% of the total), followed by industrial firewood (25%), wood industry (15.5%), charcoal sector (11%), reconstituted panels (6.5%), treated wood (0.6%), and others (1.0%)^[3].

The productivity increases of most commodities have been attributed to the increasing use of agrochemicals^[7,8]. For example, fertilizer consumption increases every year (between 30 and 35 million tons

Table 1. Planted area, productivity, and estimated production of some commodities in Brazil for the 2021/2022 harvest

Crop	Area (ha)	Productivity (kg/ha)	Production (in 1000 t)
Soybean ¹	40,351.7	3539	142,789.9
Maize ¹	20,939.3	5596	117,181.5
Beans ¹	2907.9	1079	3136.6
Sugarcane ¹	8264.4	68,780	568,430.2
Coffee ²	1,808,462	1584	2,862,960
Cocoa ³	581,884	446	259,310

¹Estimated area in 1000 ha (source: CONAB^[4]). ²Coffee productivity in 26.4 bags per hectare (1 bag = 60 kg). Coffee production in 47,716 million bags (source: CONAB^[4]). ³Cocoa production in tons in the year 2019 (259,310 t = 259,310,000 kg) (source: Gama-Rodrigues *et al.*^[5]).

during the period 2013-2020) in view of the advancement of agriculture in the country and the need to increase productivity in mostly low fertility and very acidic soils. While Brazil's fertilizers supply the domestic agricultural sector, the demand is much greater than the production capacity of the national industry^[7]. Other inputs (pesticides, herbicides, *etc.*) follow the same trend as fertilizers, as their consumption has increased by approximately 380% between 2000 and 2019. The inappropriate use of these inputs compromises the growth of the Brazilian agricultural and forestry sector in terms of the quality of the environment and the product generated.

Greenhouse gas emissions

Emissions in the agricultural sector are mainly from the digestion of ruminant animals, which emit methane (enteric fermentation), and the management of waste from these animals. GHG emissions also derive from the cultivation of irrigated rice, burning of agricultural residues, sugarcane and cotton cultivation, and those originated from the way agricultural soils are managed, considering the increase in nitrogen through the use of agricultural inputs and operations^[1].

Agricultural sector emissions have increased by 47.8% since 1990, mainly due to farmland management (+109%) by the use of synthetic and organic fertilizers, the management of animal waste (+58.6%), and due to increases in the population of cattle (enteric fermentation, +31.9%). There was a small increase in the contribution of irrigated rice cultivation (+11.8%); however, there was a drastic reduction in burning agricultural residues (-80.4%) [Table 2]. Enteric fermentation (methane) was responsible for 64.6% of gross GHG emissions in 2020, followed by agricultural soil management (28.8%), manure management (4.7%), rice cultivation (1.8%), and burning of agricultural residues (0.1%) [Table 2]. Agricultural soil management is the main N₂O emitter into the atmosphere, accounting for 85% of the country's total due to waste deposition in the soil and application of nitrogen fertilizers, with a direct influence on increasing the productivity of national livestock and agriculture production^[9]. Additionally, direct manure deposition on the soil by animals in pastures contributes to 34% of emissions from managed pasture soils, followed by the application of organic fertilizers (30%), synthetic fertilizers (24%), agricultural residues incorporated into the soil (9%), and management of organic soils (3%)^[10].

Several studies have been developed in the last 20 years to measure the potential for GHG emissions in sugarcane production^[11], irrigated rice^[12], maize^[13], soybeans^[14], beans^[15], integrated crop-livestock system^[16], oranges^[17], beef cattle^[18], agroforestry systems^[19], eucalyptus^[20], and other land uses^[21]. All of these case studies evaluated different soil management practices, with the emphasis on applying different sources of synthetic nitrogen fertilizers and the use of animal waste, seeking to develop specific methods for measuring GHG emissions suited to the environmental conditions of each production system [Table 2].

Table 2. Estimate of GHG emissions from agriculture in Brazil (TCO₂eq - GWP AR5)

Emission factor ¹	1990	2000	2010	2020
Enteric fermentation	282,683,055 (72.4)	312,364,176 (71.3)	368,496,315 (69)	372,973,344 (64.6)
Rice cultivation	9,272,835 (2.4)	10,311,099 (2.4)	10,793,789 (2)	10,369,554 (1.8)
Management of animal waste	17,022,803 (4.4)	18,201,021 (4.2)	22,843,859 (4.3)	26,996,464 (4.7)
Burning of agricultural residues	1,886,873 (0.5)	1,794,206 (0.4)	2,055,441 (0.4)	369,800 (0.1)
Managed soils*	79,587,469 (20.3)	95,386,419 (21.7)	129,884,998 (24.3)	166,313,837 (28.8)
Total	390,453,035	438,056,921	534,074,403	577,022,998

¹Adapted from Potenza *et al.*^[1]; the numbers in parentheses represent the annual percentage of each emission factor; *input addition - particularly nitrogen fertilizers.

Carbon footprint

As a result of human activities, significant increases in GHG emissions around the world have led to the development of the concept of the carbon footprint (CF). Carbon footprint corresponds to the amount of GHG (expressed in CO₂eq) emitted for the production of a commodity unit during a given period, and CF makes it possible to establish changes in production systems to meet the goals of low-carbon agriculture^[22]. The important thing for measuring the CF of a crop or product is to consider all activities and inputs at various stages of the production chain: inputs of fertilizers, herbicides, pesticides, and others (inherent in the specifics of different production systems); the use of fuel and energy in field operations; irrigation and transport of inputs to the farm; and harvested products and co-products from the farm to their processing or storage locations. This assessment also takes into account production data, waste management, and soil characteristics, as well as C stock and other management decisions (type of crop, cover crops, and land conversion)^[23].

Few studies have evaluated the CF in Brazil, mostly restricted to case studies at the farm scale. Several methodologies have been used in these studies seeking to meet the specificities of each evaluated production system. As a result, different GHG emission factors were considered in the CF calculations, which make it difficult to obtain a national standard for the agricultural sector's production chains.

DISCUSSION

Strategies and challenges for low-carbon agriculture

The Brazilian government created the Sectorial Plan for Mitigation and Adaptation to Climate Change in 2009, being called the Low-Carbon Agriculture (LCA) Plan [*Plano Agricultura de Baixa Emissão de Carbono (ABC)*], as part of the commitment to reduce GHG emissions, assumed at the 15th Conference of the Parties in Copenhagen. The LCA Plan supports 5 million rural households across the country and aims to ensure the continuous and sustained improvement of management practices, which reduce GHG emissions and additionally increase the fixation of atmospheric CO₂ in the plant-soil system of the various sectors of Brazilian agriculture. Examples of sustainable technologies and systems for agricultural production include no-tillage (NT), agrosilvopastoral systems, recovery of degraded pastures, biological nitrogen fixation (BNF), and tree plantations^[24,25].

The expansion of the LCA Plan promoted an increase in the area of integrated production systems from 5.5 to 11.5 million hectares from 2010 to 2015, of which 83% with agropastoral systems, 9% with agrosilvopastoral, and 7% with silvopastoral systems^[26]; expansion of the NT area by approximately 36 million hectares in 2018^[27]; and a 166% increase in areas with BNF in the period from 2010 to 2020, totaling 14.6 million hectares. Among the partially met targets is the expansion of 1.9 million hectares of tree plantations during the period from 2010 to 2020, corresponding to 60%-76% of the target^[1]; an increase of

13.2 million hectares in the recovery of degraded pastures, the target being 15 million hectares; and partial compliance of only 39% expansion in the use of technologies for treating animal waste^[1].

Today, the LCA in Brazil is a reality with favorable results on C sequestration and reduction of CF in different land use systems. This has been achieved through strategies focused on sustainable development and the conservation of natural resources. Such strategies have promoted the reduction of GHG emissions by 6.1 million (TCO₂eq - GWP AR5) through tree plantations, 50.6 million (TCO₂eq - GWP AR5) through an integrated crop-livestock-forest system, 53.6 million (TCO₂eq - GWP AR5) through no-till practices, and 105 million (TCO₂eq - GWP AR5) through well-managed pastures^[1].

The great challenge for the expansion of LCA in Brazil is the integration of environmental criteria, technical assistance, and financial credit. In this sense, there are still many cultural, technical, and financial obstacles that discourage farmers, especially small farmers, from adopting these sustainable practices. The lack of access to technology, knowledge, and interest (risk aversion) in LCA practices, as well as difficulties accessing credit or loans, are a consequence of little or non-existing technical assistance to support farmers in adapting their production systems.

The current state of knowledge of CF under major agricultural systems in Brazil

Beef cattle production

The beef cattle production system is the most studied due to the constant pressure to reduce GHG emissions. Enteric fermentation in central-west and southern Brazil contributed more than 90% of the CF^[18,28]. In contrast, the contributions from inputs, fossil fuels, and electricity contributed 1%-11%^[18]. Additionally, the conversion of degraded pasture to a well-managed pasture and the introduction of crop-livestock-forest integration system (CLFIS) can reduce the CF of beef cattle by 5.9 kg CO₂eq per kg LW (live weight) in CLFIS and 9.1 kg CO₂eq per kg LW in the managed pasture, without taking into account the technical potential for C sequestration in the managed pasture (soil C) and CLFIS (soil C and *Eucalyptus* biomass C). Considering the potential for soil C sequestration in the managed pasture and CLFIS, the CF of beef cattle could be reduced to 7.6 and 28.1 kg CO₂eq per kg LW in managed pasture and CLFIS, respectively^[29].

In turn, other studies have shown that some practices can be adopted to reduce the CF: (1) supplementation of the animal's diet with rations in the dry season, as this enables greater live weight gain during this phase; (2) reducing the slaughter weight, which subsequently reduces the animal's grazing time; (3) increasing the weaning rates; (4) pasture management with the introduction of legumes, which reduces the need for nitrogen fertilization, in addition to improving the nutritional quality of food; (5) introduction of high-yielding tropical forage species and intensively managed pastures; (6) introduction of winter and summer grasses; (7) improving the forage nutritive value; (8) replacing road transport units with more modern vehicles in the industrial phase; and (9) implementing an integrated crop-livestock system^[28,30].

The confinement system in dairy cattle production in southern Brazil presented lower CF when compared to the semi-confinement and pasture-based system (CF per kg of milk with energy correction). The factor which most contributed to CF in the confinement and pasture system was enteric fermentation, while in semi-confinement, it was the type of cattle feed^[31].

*Common bean (*Phaseolus vulgaris*)*

Regarding beans, the CF per kilogram of beans produced in an integrated production system was 7.4% lower than that in a conventional system due to the use of inoculants to replace synthetic nitrogen

fertilization^[32]. This study concluded that this little difference in CF between systems indicates the need to seek improvements in agronomic practices of integrated systems aiming at better results.

Soybean

In the case of Brazilian soybean, the results presented by Escobar *et al.*^[33] show great variability due to differences in land-use dynamics, growing conditions, and supply chain configurations up to the stage where soybean and its derivatives are delivered to importing countries. These authors and Persson *et al.*^[34] highlighted that the loss of natural vegetation related to land-use change was the factor that contributed most to the increase in CF in soybeans. Additionally, Lathuilière *et al.*^[35] pointed out that the decline in deforestation in the Mato Grosso region in the first decade of this century suggested a change in the soybean production system from an extensification system (agricultural expansion in natural ecosystems) to one based on intensification (increased productivity of the available land), which led to an increase in CF for this crop, even though there is no application of nitrogen fertilization due to the practice of inoculation with nitrogen-fixing bacteria and Brazilian soybeans are planted in a no-tillage system^[24].

Vegetable crops

Pereira *et al.*^[36] found interesting results in vegetable crops. The CF to produce 1 kg of vegetables in a consortium was approximately one-fifth that of monocultures, and sharing infrastructure (construction of greenhouses) and optimizing inputs in the consortium were the main GHG mitigators. They also stated that producing vegetables in a greenhouse, predominantly carried out in monoculture, significantly contributes to GHG emissions associated with agriculture in Brazil. The CF was also evaluated in yellow melon exporting farms (they account for about 99% of Brazilian exports), and the estimated value was 710 kg CO₂eq/t of exported melon. The authors suggested that this value could be reduced by 44% if melon production were located in pre-existing agricultural areas, as nitrogen fertilization would be reduced and no plastic trays would be used in melon production^[37].

Coffee and Cocoa-cabruca AFS

In coffee monoculture, the CF represents 5% of emissions in the southeast region of Brazil related to agriculture, with the use of water for irrigation being the main factor that contributes to the increase in CF^[38]. Martins *et al.*^[38] suggested that carbon sequestration in coffee tree biomass should be considered to reduce the CF. Schroth *et al.*^[39] found that agricultural intensification in cocoa-cabruca AFSs (cocoa plantations implanted under natural forest) in southern Bahia reached twice the regional average yield mainly through mineral fertilization, which was compatible with maintaining a low CF related to inputs, close to 0.25 kg CO₂eq kg⁻¹ of cocoa seeds. They also demonstrated that shade tree management (a shade level of up to 55%) could increase C stocks in plant biomass, thus constituting another positive contribution to climate change mitigation, which could add conservation value to cabruca systems in Bahia.

All of these case studies indicated the main sources of greenhouse gases in some products of Brazilian agriculture at the farm scale. However, we need to develop research lines for an integrated assessment of the different land use systems at a landscape scale in the different biomes for a better understanding of agricultural production in the context of the environmental impacts and sustainability of the production chain. Thus, we can enter the low-carbon agriculture route, aiming to protect the environment for future generations while meeting urgent needs for food.

Compensation for GHG emissions

Compensation of GHG emissions can also be achieved by carbon sequestration (C); in particular, soil C stock, as a process of converting atmospheric CO₂ into stable soil organic C through forming organomineral

complexes, can compensate for GHG emissions, mainly because soil stores 2-3 times more C than the atmosphere. Studies on soil C stock as a measure to offset GHG emissions have grown in Brazil, with a wide range of 20-460 Mg C ha⁻¹ [Table 3]. This wide variation in C stocks is due to the adopted management systems, the soil texture, relief, sampling depth, age of land-use systems, climate conditions, land-use history, and chemical composition of plant residues.

Agricultural land under no-tillage, mainly in crop rotation or intercropping systems, plays an important role in promoting soil erosion control and reducing soil organic C losses, favoring aggregation and, therefore, soil C stabilization through greater physical protection against the action of microorganisms^[24,40]. Besides, the adoption of no-till and no burning of crop residues can help to restore soil carbon, particularly during the summer season and when farmers leave large amounts of crop residues on the soil surface.

Land-use systems based on trees and pastures (well managed and/or under grazing) showed a higher soil C stock due to the continuous addition of residues (above- and below-ground), and also because most of them have not suffered from soil disturbance for over 20 years. It is worth mentioning that pasture management (by reducing stocking rate and/or using a mixture of pastures) promoted an increase of close to 40% in the C stock up to 1 m depth [Table 3]. Salgado *et al.*^[41] reported that the C stock at 1 m depth in the soil under rubber plantation was 51 and 89 Mg ha⁻¹ higher than the stocks of rubber tree + açai and rubber tree + cacao agroforestry systems (AFSs), respectively, in southern Bahia, Brazil. However, the AFSs showed a higher amount of stable C (in the range of 41%-54% of C occluded in macro- and micro-aggregates) than the rubber tree plantation (32%). These results emphasize aggregates as a C storage compartment in the soil, and therefore the relevance of evaluating the extent of C storage in different fractions of soil aggregates up to 1 m depth. Thus, to increase the C reservoir in the soil, it is necessary to adopt management practices that favor a positive C balance and its persistence in the soil. In this sense, conservationist production systems must be adopted on a large scale in order to mitigate GHG emissions in the Brazilian agricultural and forestry sector.

Brazil is one of the few countries in the world that integrates in the same area different production systems (grain, fiber, bioenergy, livestock, and forest production) in a consortium, rotation, or succession, with mutual benefits for all activities. This technology optimizes land use, increases productivity, provides market product diversification, plays an important role in food security and the efficient use of natural resources, and is a viable strategy to improve farm income. Thus, these integrated systems constitute a landscape mosaic with enormous potential for reducing CF.

In this context, we highlight the multistrata agroforestry systems that present a forest-like structure with a highly diversified landscape that could be interconnected by forest remnants. They are a potential supplier of fruits, firewood, wood, latex, fodder, and ecosystem services for increasing biodiversity and promoting soil health, and improving water quality, in addition to the benefits mentioned above^[4]. These systems would be an appropriate technology for improving the living standard of household in an agricultural region that would be based on the natural resources conservation and, therefore, promising for the consolidation of climate-friendly agriculture [Figure 2].

CONCLUSIONS AND PERSPECTIVES

Sustainable rural development programs and activities are increasing in Brazil with the improved adoption of the LCA Plan technologies, resulting in a 154% expansion in area and a 113% increase in CO₂ mitigation in the atmosphere. These activities are currently confined to some regional segments and a small number of farmers, but they should be disseminated for wider adoption on a national scale. To achieve this, it is

Table 3. Soil C stock (Mg ha⁻¹) under different land-use systems

Land use systems	Bioma	Depth (cm)	C stock	Ref.
CT - sugarcane	Cerrado; Atlantic Forest	100	77-168	Oliveira <i>et al.</i> ^[42]
CT - soybean	Cerrado	30	~50	Siqueira-Neto <i>et al.</i> ^[43]
CT - crop rotation	Cerrado	30	50-60	Carvalho <i>et al.</i> ^[44]
CT - maize	Cerrado	100	~78	Santos <i>et al.</i> ^[45]
NT - crop rotation	Cerrado	30	60-65	Siqueira-Neto <i>et al.</i> ^[43]
NT - intercrop	Cerrado	40	45-60	Gmach <i>et al.</i> ^[46]
NT - maize	Cerrado	100	~79	Santos <i>et al.</i> ^[45]
Pasture	Amazon Cerrado	30	55-75	Siqueira-Neto <i>et al.</i> ^[43] Carvalho <i>et al.</i> ^[44] Rittl <i>et al.</i> ^[47]
Pasture	Cerrado	40	70-75	Gmach <i>et al.</i> ^[46]
Pasture	Cerradão	100	100-460	Oliveira <i>et al.</i> ^[42] Pinheiro <i>et al.</i> ^[48] Tonucci <i>et al.</i> ^[49]
Pasture	Atlantic rainforest	100	150-220	Salgado <i>et al.</i> ^[41] Oliveira <i>et al.</i> ^[50] Monroe <i>et al.</i> ^[51] Vicente <i>et al.</i> ^[52]
Integrated crop-livestock system	Cerrado	30	60-73	Carvalho <i>et al.</i> ^[44]
Silvopasture	Cerrado	100	19-420	Pinheiro <i>et al.</i> ^[48] Tonucci <i>et al.</i> ^[49]
Cacao cabruca AFS	Atlantic rainforest	100	180-330	Monroe <i>et al.</i> ^[51] Gama-Rodrigues <i>et al.</i> ^[53]
Cacao + erithrina ¹ AFS	Atlantic rainforest	100	174-310	Oliveira <i>et al.</i> ^[50] Monroe <i>et al.</i> ^[51] Gama-Rodrigues <i>et al.</i> ^[53]
Cacao + rubber tree AFS	Atlantic rainforest	100	92-206	Salgado <i>et al.</i> ^[41] Oliveira <i>et al.</i> ^[50] Monroe <i>et al.</i> ^[51]
Rubber tree + Açai ² AFS	Atlantic rainforest	100	~130	Salgado <i>et al.</i> ^[41]
Rubber tree plantation	Atlantic rainforest	100	180-220	Salgado <i>et al.</i> ^[41] Oliveira <i>et al.</i> ^[50] Vicente <i>et al.</i> ^[52]
Eucalyptus	Cerrado	40	~50	Gmach <i>et al.</i> ^[46]
Eucalyptus	Cerradão	100	180-404	Pinheiro <i>et al.</i> ^[48] Tonucci <i>et al.</i> ^[49]
Eucalyptus	Atlantic rainforest	100	145-160	Vicente <i>et al.</i> ^[52]
Native vegetation	Cerrado	30	63-75	Siqueira-Neto <i>et al.</i> ^[43] Carvalho <i>et al.</i> ^[44]
Native vegetation	Cerrado	40	~75	Gmach <i>et al.</i> ^[46]
Native vegetation	Cerrado	100	75-94	Santos <i>et al.</i> ^[45]
Native vegetation - an intermediate Cerrado with trees	Cerradão	100	94-414	Oliveira <i>et al.</i> ^[42] Pinheiro <i>et al.</i> ^[48] Tonucci <i>et al.</i> ^[49]
Natural forest	Amazon	30	56-70	Carvalho <i>et al.</i> ^[44] Rittl <i>et al.</i> ^[47]
Natural forest	Atlantic rainforest	100	83-260	Salgado <i>et al.</i> ^[41] Oliveira <i>et al.</i> ^[50] Monroe <i>et al.</i> ^[51] Vicente <i>et al.</i> ^[52] Gama-Rodrigues <i>et al.</i> ^[53]

¹*Erythrina* sp.; ²*Euterpe oleracea*. CT: Conventional tillage; NT: no tillage.

necessary to involve the local community, local and national NGOs, the private sector, and federal and municipal agencies and intensify public policies for access to rural credits and innovations in diffusing



Figure 2. Multistrata agroforestry systems as a model of low-carbon agriculture in Brazil: (A) cacao + rubber tree with food crops in the initial phase; (B) cacao + rubber tree in the mature phase; and (C) cacao + coffee + peach palm.

technologies. Large-scale adoption of conservationist agriculture practices by the farming community will generate economic opportunities leading to financial gains from the commercialization of carbon credits and payment for environmental services.

On the other hand, the challenge of low-carbon agriculture in Brazil is to expand the production of food, bioenergy, and other products to meet future demands with less dependence on the use of inputs while also saving land and protecting natural ecosystems. To do so, future research actions to reduce carbon footprints should prioritize sustainable intensification through a combination of agricultural intensification (production value) with ecological intensification (conservation value) at the landscape scale. High emphasis should be placed on the role of biological processes in controlling pests and diseases and on nutrient cycling for maximizing the input-use efficiency, thereby allowing a sharp reduction in production costs. In turn, this can increase the economic and ecological resilience of agricultural regions in Brazil. In this context, low-carbon agriculture can be considered an environmentally friendly and climate-smart technique.

DECLARATIONS

Authors' contributions

Conceived and wrote the manuscript: Gama-Rodrigues EF, Gama-Rodrigues AC

Responsible for the figures and graphical abstract: Alvarenga LCBR

Responsible for data collection: Gama-Rodrigues EF, Gama-Rodrigues AC, Vicente LC, Müller MW, Partelli FL, Gonçalves JLM, Freitas LS, Alvaristo DM, Cruz IB, Souza ING, Faitanin MA

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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