Chapter 8
The Brazilian Way of Farming: Potential and Challenges to Agricultural Decarbonization

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Abstract Mitigating GHG emissions through different low-carbon agricultural interventions has gained widespread attention, and Brazil can play an important role in this regard. For this, specific institutional and technical means should become increasingly context-sensitive, which is essential to provide precise standards and measures adapted to tropical agriculture. Nevertheless, any operational framework must be founded on strong science, rigorous adherence to the standards of integrity, and reliable MRV approaches. Carbon pricing could promote initiatives to support low-carbon agriculture in Brazil if it is appropriately founded on those principles. This chapter offers an overview of Brazilian agriculture's engagement in carbon market mechanisms while highlighting the potential and issues related to legal framework, cultural and technical barriers, measurement, reporting, and verification difficulties, as well as coordination requirements. We conclude by presenting general recommendations.

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8.1 Introduction

The promotion of the transition towards deep decarbonization of economies worldwide is urgently needed. In this respect, carbon pricing can play an important role in internalizing costs of greenhouse gas (GHG) emissions amongst the responsible economic agents fostering incentives towards mitigation initiatives. Brazilian GHG emissions related to land use change and agriculture account for around 75% of total domestic emissions. Agriculture is tightly interconnected with environmental risks related to land use change, water scarcity, phosphorus and nitrogen cycles, biosphere integrity, and climate change (Springmann et al., 2018; Willett et al., 2019). Moreover, expansion of the agricultural production of commodities such as beef, soybeans, and palm oil is often associated with processes of land use change with detrimental climate impacts (Henders et al., 2015; Pendrill et al., 2019). Thus, important contributions to the climate agenda could be made if proper incentives were created to encourage more sustainable practices.

Efforts to mitigate the undesirable effects of agriculture on the global climate system have gained widespread attention, encompassing different interventions, ranging over sustainable intensification, agroforestry experimentation, precision fertilizer application, decoupling of food production from deforestation through increasing productivity, and other changes in the conventional modes of production and consumption. A transition in the direction of low-carbon agriculture can, thereby, become an essential force for change in global climate mitigation efforts. The dimension of area used to pastures, crops, and planted forests in Brazil – nearly 240 million hectares – creates huge opportunities to conduct high-impact sector-wide decarbonization schemes. The potential of Brazilian agriculture to sequester carbon in soils comes from the possibility – existent in the tropics and subtropics – of increasing soil carbon inputs through improved productivity and the cultivation of up to three different crops throughout the year on low tillage. The management of different crops, including cover crops and crop-livestock production is, however, a great challenge due to the heterogeneity of soils and climates, and the huge variation between the most and less emissions-intensive modes of production in Brazil.

This chapter provides an overview of the current state of the engagement of the Brazilian agricultural sector towards carbon pricing and market mechanisms and highlights the opportunities and challenges in terms of lowering sectoral emission levels. While carbon pricing is an important step to promote economic incentives in favour of low-carbon development (Edmonds et al., 2019; High-Level Commission on Carbon Prices, 2017; van den Bergh & Botzen, 2020), scholars have also cautioned about the risks of relying on market mechanisms, especially with respect to the integrity of emission reductions (Green, 2017; Ervine, 2018; Schneider & La Hoz Theuer, 2019; Schneider et al., 2019). In this sense, we aim to provide an outlook on existing efforts and the future potential to spur emission reductions through carbon pricing in the Brazilian agricultural sector.

First, we present some key data on Brazil's emission profile and its potential with specific regard to the opportunities and comparative advantages for the Brazilian agricultural sector to engage in the carbon markets. Then we describe and analyse some of the most important challenges in this regard, related to regulatory frameworks, cultural obstacles, measurement, reporting and verification challenges, and coordination needs. The conclusion sums up the results and presents some general recommendations.

8.2 Natural Climate Solutions: Brazil Within the Global Context

Brazil's dimension and natural resource endowments could provide certain comparative advantages for the country within the context of global carbon markets. The country's course of action is globally relevant to either aggravate or mitigate the climate crisis. Farmers could thereby become part of the solution, as a huge potential exists either through the conservation of the native vegetation within farm boundaries or by the adoption of more climate smart and land-intensive production models, introducing practices that increase soil carbon stocks.

Natural climate solutions (NCS)[1] have attracted significant attention as a manner of reducing GHG emissions from ecosystems and harnessing their potential to store carbon (Seddon et al., 2020). In this context, tropical countries deserve attention, as they hold around 60% of the global NCS potential. Brazil accounts for at least 21% of the tropical NCS potential at "cost-effective" levels (<100 USD Mg CO_2eq^{-1}) (Griscom et al., 2017, 2020). Crucially, the country responds approximately to 15% of the entire global NCS potential (McKinsey Nature Analytics, 2021). Despite the great potential of climate change mitigation outcomes related to forest resources, Brazil also has significant mitigation options related to agriculture and land management, which represents 14% of the total (Griscom et al., 2020).

Brazilian emissions from agriculture, land use change, and forestry account for 74% (Fig. 8.1) (SEEG, 2022a).[2] From the emission profile of Brazilian agriculture

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[1] NCS refer explicitly to conservation and management initiatives that reduce GHG emissions and store carbon falls under the umbrella of nature-based solutions (NbS). These in turn rely on enhancing natural activities to help address societal challenges, encompassing a wide range of actions, such as the protection and management of natural and semi-natural ecosystems, the incorporation of green and blue infrastructure in urban areas, the application of ecosystem-based principles to agricultural systems, and so on (Seddon et al., 2020).

[2] The data comes from SEEG (Greenhouse Gas Emission Estimation System), by the Brazilian NGO network Climate Observatory (Observatório do Clima). The estimates cover GHG emissions in Brazil and in each of the states and the federal district for the period 1970–2021 for all sectors, except for land use change, which covers the period from 1990 to 2021. It considers all GHGs contained in the national inventory as CO_2, CH_4, N_2O, and HFCs in the metric GWP (global warming potential) and according to the conversion factors set in the 5th IPCC report (AR5). The methodological basis of the SEEG estimates (De Azevedo et al., 2018) is the 4th Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions and Removals. See more at: https://seeg.eco.br/en/entenda-as-estimativas

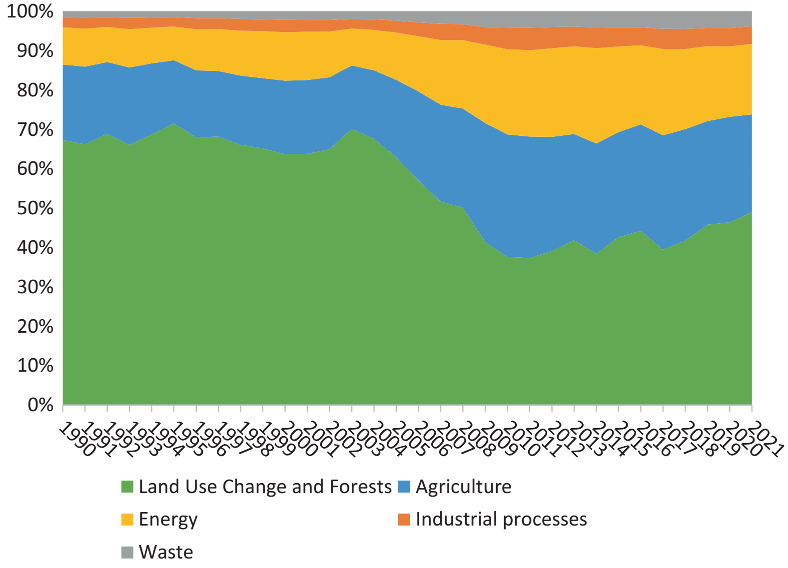

Fig. 8.1 Historical evolution of the Brazilian emissions by source, in % of the total. (Reproduced from SEEG, 2022a)

(excluding land-use change), it can be observed that activities such as livestock production (through enteric fermentation) and soil management account for the main share of sectoral emissions (Fig. 8.2). Consequently, sustainable intensification of livestock, recovery of degraded pastures by conversion to well-managed pastures, low-carbon agriculture and/or reforestation, adoption of integrated systems, and strategies to reduce nitrogen fertilization are important parts of the solution for the country's engagement in the climate agenda.

The soil is one of the greatest carbon reservoirs on the planet and can thereby function as a net sink of CO_2 being regarded as a NET (negative emission technology). The global potential of soil organic carbon (SOC) sequestration is estimated at 1.45–3.44 GtC year^{-1} (5.3–12.6 GtCO$_2$ year^{-1}) (Lal, 2018). In 2020, this represented between 10% and 23% of the total global emissions (54 GtCO$_2$ year^{-1}) (UNEP, 2022). As much as 25% of the global NCS potential can be found in soils, which in turn represent 47% of the mitigation potential of agriculture (including grasslands). Additionally, multiple ecosystem services can be delivered through sustainable soil interventions and management practices (Bossio et al., 2020). Brazil has one of the biggest potentials for storing carbon in the soil, according to FAO (2022). Specifically, 12.7% of total yearly relative SOC sequestration potential at 30 cm based on a high carbon inputs sustainable soil management scenario.

Nonetheless, prevailing NET options, such as afforestation/reforestation, coastal blue carbon, sustainable forest management, agricultural soils, and bioenergy with carbon capture and sequestration, are still incapable of providing sufficient negative

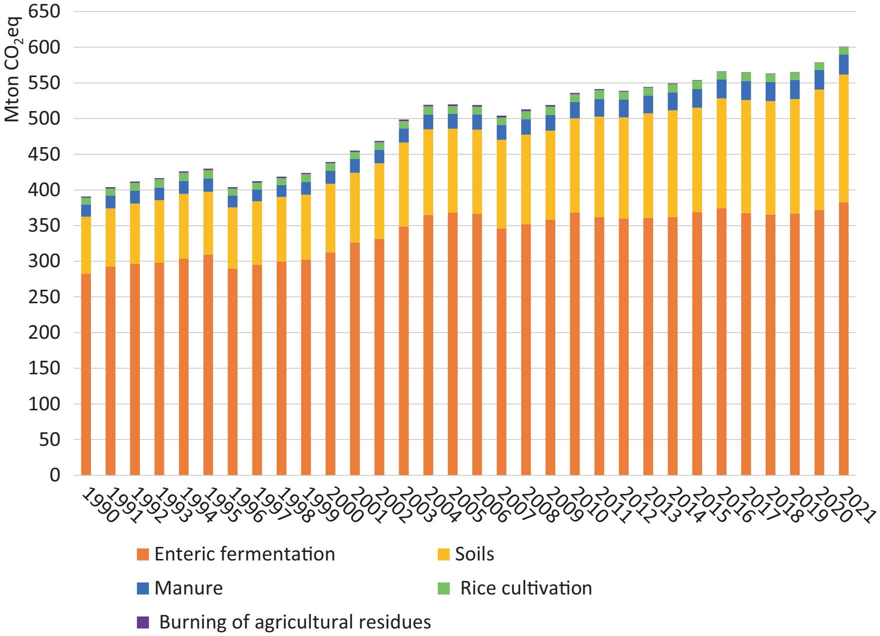

Fig. 8.2 Emissions from Brazilian agriculture by source, excluding land use, in Mt CO_2eq (Emissions computed as "soils" or direct emissions from agriculture derive from the way in which agricultural soils are managed, considering the increase in Nitrogen through the use of inputs and agricultural operations (managed soils). These N_2O (nitrous oxide) emissions, comprise those coming from the use of beef cattle manure used as fertilizer along the pasture, together with the use of synthetic fertilizers, and CO_2 emissions and liming emissions). (Reproduced from SEEG, 2022b)

emissions at low costs. Therefore, substantial R & D investments are necessary to improve current NETs and lower their costs (National Academies, 2019). Climate financing for soil is undergoing rapid developments, and the Paris Agreement has adopted an explicit focus on agriculture. Since 2018, the Koronivia Joint Work on Agriculture under the UNFCCC has looked into the mitigation potential of soils and agriculture, comprising SOC practices, including soil health and fertility under grass and cropland, as well as crop, livestock, and forestry integration (UNFCCC, 2018). Many new private sector initiatives related to SOC have also been launched, which could provide important funding and results (Bossio et al., 2020).

Photosynthesis and respiration determine net primary productivity – which is how much carbon dioxide vegetation takes in during photosynthesis minus how much carbon dioxide plants release during respiration, i.e. the amount of C available for production (NASA Earth Observations, 2022). Tropical regions are frequently marked by intermediate SOC levels, because of a combination of higher primary productivity potential throughout the year, higher lignin content, but increased decomposition rates in high temperatures and extensive rainfall. While climatic conditions are important in determining global soil carbon patterns, factors varying on smaller spatial scales together with climatic conditions also define SOC levels.

For instance, soil texture – referring to relative proportions of silt, sand, and clay particles constituting the specific soil – or the soil mineralogy of those particles can have an important effect on carbon stocks. Moreover, erosion and deposition redistribute soil carbon depending on the topography within a particular landscape. Low-lying areas, for example, floodplains, often display increased SOC relative to upslope areas (Ontl & Schulte, 2012). Furthermore, high levels of insolation differentiate crop frequency within tropical agricultural contexts. The technological model of cultivation in Brazil – greater crop rotation given the crop frequency – enhances productivity and, consequently, faster carbon accumulation in the soil. Thus, the differential of soil carbon stock change in the Brazilian conditions derives mainly from the potential to increase the rate of biomass addition throughout the year (Nicoloso & Rice, 2021).

8.3 Comparative Advantages and Opportunities for the Brazilian Agricultural Decarbonization

Brazil could become a key supplier of carbon credits through the conservation of natural vegetation, through reforestation, and with the adoption of more modern land cultivation practices at a low cost per ton of CO_2 sequestered. Brazil has shown significant potential though REDD+ initiatives, although project development so far has been complex. Reforestation can complement improved agricultural production through environmental co-benefits, such as the preservation of biodiversity and water resources. These co-benefits also mean that carbon credit generation is the only one amongst many possible ecosystems' gains. Companies specialized in developing carbon sequestration projects from forest preservation have gained momentum in Brazil. Furthermore, interest in projects to regenerate private properties' legal reserves of native vegetation has fostered a second wave of companies, providing restoration of deforested areas. In both models, the commercialization of carbon offsets related to avoided deforestation and reforestation, respectively, generates a revenue from carbon credits providing income for the landowners.

Another comparative advantage concerns the mitigation potential through the implementation of sustainable agricultural land management to increase soil carbon stocks. Many farmers are unfamiliar with the many existing sustainable practices. This leaves room for improvement through the broad dissemination of these sustainable interventions. Raising the level of soil organic matter is critical, as this both increases productivity gains and sequesters carbon.[3] Mitigation estimates for NCS interventions vary, and different trade-offs and co-benefits exist. Practices such as

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[3] Soil carbon stocks and soil organic matter (SOM) are closely related. SOM contains a complex mineral-organic matrix with compounds having diverse carbon functional groups and a varied structure and content. As a result, C is strongly correlated to SOM, making soil organic carbon (SOC) a reasonable predictor of SOM. Other SOM elemental components are found in the mineral-organic matrix with less consistency and abundance than carbon (Roper et al., 2019).

cover cropping, no-till, enhanced crop rotations, and pasture management area activities each with very different feasibility levels and potential impacts on SOC and N_2O emissions. Measures to raise organic carbon in one soil type might be ineffective in other soil types (Bossio et al., 2020). As a carbon sink, the soil carbon levels tend to achieve a steady state after 20–30 years of proper management, which could change again if different practices are carried out. In the following paragraphs, we briefly list agricultural land management practices, roughly outlining their potential for coverage in terms of area, mitigation, and co-benefits:

8.3.1 No-Tillage

Brazil is amongst the countries where the practice of no-tillage (NT) is most widely adopted. Around 35 million hectares – or about 60% of grain crops – in Brazil implemented NT (Fuentes-Llanillo et al., 2021). This is equivalent to around 85–90% of the entire soybean area in Brazil (Embrapa, 2018). NT improves soil quality and climate change adaption of agriculture, but its mitigation effects are less consensual (Powlson et al., 2014), depending on the previous type of land use. Findings from different Brazilian regions show that when adopted from conventional tillage or pasture, NT promotes carbon sequestration in agricultural soils. The SOC storage is not restricted to the soil top layer (0–30 cm) but is also effective up to 50 cm in depth, with gains varying between 9% and 25% (Maia et al., 2022). Furthermore, when combined with higher crop frequency and the use of cover crops, no-tillage can increase soil carbon sequestration, raising soil quality, and climate change adaptation (Nicoloso & Rice, 2021). Conservation agriculture encompasses three fundamental principles: (a) crop diversification and/or rotations and/or associations, (b) no-tillage, and (c) permanent soil cover. When these principles are applied together within the so-called no-tillage system, the efficiency of no-tilling to increase soil organic matter increases. Compared to conventional practices relying on soil ploughing, a no-tillage systems can reduce CO_2 emissions by 0.5–0.6 tCO_2 $year^{-1}$ ha^{-1}. Considering that a complete no-tillage systems are implemented only by a small proportion of those who employ the practice, the broader dissemination, and combination with other practices, such as the integration of soy cultivation with forestry, can yield significant emission reductions for soy production (Possamai et al., 2022; Estevam et al., 2022).

8.3.2 Biological Nitrogen Fixation (BNF)

BNF relies on the use of inoculated seeds to increase plant nitrogen uptake through association with bacteria that fix atmospheric N_2 in roots, transforming it into forms that permit assimilation by plants. BNF can provide the main source of nitrogen for soybean plants along with all the nutrients needed by the crop (Hungria & Mendes, 2015). It is a more economical alternative than nitrogen fertilizers and substantially mitigates emissions produced by chemical fertilizers. In Brazil, BNF is extensively applied, resulting in savings of up to US$ 14 billion/crop on fertilizer substitution, while averting the emission of 68 $MtCO_2eq$ $year^{-1}$ (Estevam et al., 2022; Nepomuceno, 2020).

8.3.3 Crop-Livestock-Forest Integration (CLFi)

CLFi occupies an area of approximately 17 million hectares (Polidoro et al., 2020).[4] This production system has a positive effect on soils by increasing nutrient retention and cycling, carbon and nitrogen contents, and water retention and reducucing soil loss due to erosion. Trees also offer thermal comfort for the livestock and ensure economic diversification, with environmental, productive, and social benefits as a result. CLFi is a promising pathway to recover degraded pastures and also holds the potential for lowering the carbon footprints of beef and dairy production. It nonetheless requires an advanced technical understanding of crop, livestock, and forestry, and not least, the dynamics of these components' integration. As 83% of CLFi systems currently encompass only crop and livestock integration, the introduction of the forestry component to raise carbon sequestration is an important challenge. Expansion of forestry products markets coupled with a higher allocation of rural credit to strengthen farmers' implementation capacity, as well as technical and managerial support are fundamental to increase the adoption (Porto, 2021).

8.3.4 Sustainable Intensification Within the Brazilian Livestock Sector

Sustainable intensification comprises a range of initiatives in the livestock sector that seek to improve production efficiency. Of Brazil's 160 million hectares of pastures, around 90 million are in some state of degradation (LAPIG, 2022). With the increase in the efficiency of cattle ranching, extensive land resources could thus be freed for either improved agricultural cultivation or reforestation projects. Transitions to well-managed pastures or CLFi systems can increase productivity by as much as 400–500% and reduce emissions with 4 tCO_2 $year^{-1}$ ha^{-1} while simultaneously capturing 6 tCO_2 $year^{-1}$ ha^{-1}. Reduced slaughter time through genetic improvement is another key part of strategies aiming at livestock intensification. Feed supplementation with the use of methane inhibitors, such as 3-Nitrooxypropanol (3NOP), essential oils, and tannins are additional steps to reduce sectoral emissions.

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[4] See chapter "Crop-Livestock-Forest Integration Systems as a Sustainable Production Strategy in Brazil" for a comprehensive content about CLFi.

The implementation of all these interventions demands massive investments, thus highlighting the potential importance of carbon-based financing in accelerating the dissemination of these practices.

8.4 Challenges and Incentives for the Engagement of Brazilian Agriculture Within Carbon Markets

A comprehensive view of the challenges and necessary incentives to engage agricultural producers in a carbon market encompasses the following three barriers: (i) the existence of a robust MRV system to measure the effectiveness of interventions, (ii) investment mobilization, and (iii) confronting governance challenges (Seddon et al., 2020). We add that an essential feature is the Brazilian government's adherence to its climate commitments by creating an appropriate institutional environment to develop carbon pricing mechanisms and a carbon market. In this section, we undertake an effort to analyse the main challenges at stake for the agricultural sector.

8.4.1 The Regulatory Environment

Brazil has historically taken early action on promoting a climate-resilient agricultural sector, providing national supply of food, fibre, and fuel, building on a range of pillars, such as knowledge based on tropical agriculture, combined with technology and policy. Domestic policies have established a stewardship commitment for globally significant carbon and biodiversity reserves (Negra et al., 2014). Brazil has invested in research to support sustainable agricultural intensification while creating legal, monitoring, and enforcement mechanisms to protect natural vegetation areas as a constraint to unbridled agricultural expansion, although challenges remain with respect to the implementation of these policies, as treated in other chapters of this volume. Next, we briefly list policy advances.

Many Brazilian stakeholders have been pioneering the development of projects within the Clean Development Mechanism (CDM) under the Kyoto Protocol, and Brazil was also amongst the first countries to establish a legal basis for the development of CDM projects (Mozzer & Pellegrino, 2018; Bittencourt et al., 2018). In 2009, Brazil instituted a national policy for climate change (*Política Nacional sobre Mudança do Clima*, PNMC, in its Portuguese acronym). In 2010, the Low Carbon Agriculture Plan (ABC Plan) was adopted, containing different measures to support mitigation efforts within the Brazilian agricultural sector. In 2021, the updated version "Plano ABC+" was launched. The Brazilian Forest Code has undergone significant changes since its origins in 1965. In 2012, its last revision was enacted[5] and in 2021, a National Payment Policy for Environmental Services entered into force. In 2019, the National Biofuels Policy (RenovaBio),[6] an incentive policy aiming at expanding biofuel use in the Brazilian energy matrix, was officially launched (Box 8.1).

At the time of writing this chapter, an allowance carbon market with obligatory mitigation objectives has not yet become consensual in Brazil. This is due to the fact that cap-and-trade systems, such as those in developed countries, have not yet been considered appropriate for the valuation of other types of ecosystem assets. A federal decree has been in force since May 2022, which constitutes a very incipient move to establish the basic institutional structures for a regulated carbon market. Important parts, such as sectorial mitigation obligations and timelines to reach reduction goals have not been clearly stated. Problems in the conceptual definitions of carbon, methane, emissions reduction credits, etc. also permeate the decree

Box 8.1: The Brazilian Low Carbon Agriculture Plan – Plano ABC+ (2021–2030)

The plan supports low-carbon agriculture encompassing a dedicated line of credit with low-interest loans and mitigating GHG emissions targets through a range of technologies. The resources allocated to the Plano ABC+ represented only 2% of the total amount of the 2022 Brazilian Crop Plan (Assad, 2022).

Technologies and adoption targets of the ABC+ Plan in terms of area and GHG mitigation

Technologies	Expansion target	GHG mitigating emissions targets (in Mt CO_2eq)
Recovery of degraded pastures	30.0 Mha	113.7
No-tillage system (complete)	12.5 Mha	13.0
CLFi and agri-forestry systems	10.1 Mha	72.0
Planted forests	4.0 Mha	510.0
Irrigated systems	3.0 Mha	50.0
Bio-inputs	13.0 Mha	23.4
Animal waste treatment	208 Mm^3	277.8
Intensive finishing slaughter	5 Mheads	16.2

Source: Mapa (2021)

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[5] See chapter “The Brazilian Forest Code: The Challenges of Legal Implementation” dedicated exclusively to the analysis of the Brazilian Forest Code.

[6] See chapter “Brazilian Biofuel Governance: The Case of Brazilian Ethanol and RenovaBio” for a comprehensive analysis of RenovaBio.

seeming to reflect objectives to integrate environmental assets within a carbon market, as normally, cap-and-trade models do not permit pricing other assets. Because of the juridically insecure nature of an executive decree, specific legislation to provide more legal certainty about the issue has been expected, with key stakeholders awaiting the developments of COP27 and the changes in the direction of the new government elected with promises of facing the climate crisis. In Brazil, most economic actors accept the need for a regulated carbon market, in part because of the possibility of the future creation of trade barriers against carbon-intensive exports.

Implementing carbon pricing in the Brazilian agricultural sector is a difficult task due to the huge number of producers, lacking land tenure registers, deficient animal monitoring and tracing systems, and informal production and marketing practices, amongst other factors. Thus, it could be necessary to exclude significant portions of the industry from early attempts to set up frameworks for carbon pricing as well as from mitigation efforts undertaken through other regulatory measures and technical support. Although a new structure of economic incentives does not necessarily imply the generation of carbon credits, they essentially alter the logic of production by incorporating environmental costs amongst producers. This serves as a crucial starting point for the adoption of low-carbon practices, which has the potential to lead to the generation of carbon credits by pioneers whose mitigation efforts go beyond legal obligations.

8.4.2 The Task of Measuring, Report, and Verify (MRV)

In the portrayed circumstances, it makes sense to measure carbon at least to a depth of one meter. However, digging trenches for soil sample collection at various layers is very time- and resource-consuming besides obvious problems for mechanization. A more cost-effective option is provided by satellite images, a technique that has seen significant improvements in recent years. Yet, this approach cannot detect carbon flows in layers below the topsoil. Another example of the complexities associated with carbon measurement in the tropics regards CLFi projects. As this involves a wide range of flows of different GHGs with varying atmospheric lifetimes of emissions produced by cropping and animals, evaluating the overall carbon balance is a complex task with several coexisting Global Warming Potential (GWP) metrics and Life Cycle Assessment (LCA) approaches impairing standardization.

This context calls for improved and more calibrated Measurement, Reporting, and Verification (MRV) procedures and technologies to prove all those aspects. For instance, studies conducted by Embrapa Forestry demonstrate that the conversion of natural pastures to forest plantations can raise carbon stocks in the soil depending on the species, their production cycle, and the local climate and soil types. Moreover, in Brazil, in general, carbon loss in soils converted to forest plantations is close to 5% and not 33%, as suggested by previous estimates (IPCC, 2006; Zanatta et al., 2020). Preliminary data – not yet published – from a carbon farming pilot initiative, indicates that a ton of soy has an average carbon footprint of 783 kg CO_2eq. This constitutes a reduction of close to 80% compared to the international databases (Embrapa, 2022a).

Large-scale adoption of MRV systems hinges on their design being sufficiently democratic to permit ample adhesion, while being robust enough to inspire confidence in carbon credits generated. Yet, the complexity of the implementation of robust MRV makes this very difficult for individual farmers. In Sect. 8.4.3, we discuss how farmer collectives could play an important role in terms of pooling MRV costs.

In 2022, the costs of measuring carbon sequestrations were often larger than the possible gains of selling carbon credits. Expensive certification, due to a range of technical barriers to MRV implementation, results in a still narrow scope for carbon projects in Brazil. Digitalization could help decrease MRV costs because of higher accuracy and lower costs related the higher data availability for calibrating dynamic models and improve statistical inference which by their turn would lead to lower demand of field measurements. Reduced costs are also expected through new emerging technologies under research for this application as several in the fields of AI, robotics, remote sensing, and the internet of things. These innovations may initially made available to more capitalized operations. Therefore, open-source public data archives of carbon stocks and flows in different regional biomes could provide important information to support MRV and production systems on farms.

Estimation of soil carbon relies on ample data to calibrate and validate carbon dynamics models, which are still scarcely available in Brazil. Accumulation of data could thereby permit the gradual improvement of models and production systems, leading to protocols with sufficient credibility and accuracy. Large-scale tools for the measurement of soil carbon (C) are needed. An alternative method to the traditional and costly dry-combustion technique is LIBS,[7] whose technology adaptation in the assessment of tropical soils, developed by the Embrapa (AGLIBS), has now been transferred to the private sector. It was approved by Verra[8] as certifiable for measuring soil carbon. This laser-based technique allows more speedy analysis at a cost of at least 50% lower (Embrapa, 2022b; Martin-Neto, 2022; Villas-Boas et al., 2020a, b). Near-infrared spectroscopy is another technique that is being used on a commercial basis in Brazil. This solution compares samples with more than 1 million analysed soil samples and AI, increasing efficiency and reducing costs (Specsolo, 2022; de Santana et al., 2019). The main challenge relates to scaling existing techniques to increase confidence and market recognition on measurement quality in all the different conditions they should be applied. This becomes critical to defining a scientifically robust standard, recognized by the market and viable for farmers.

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[7] Laser-induced breakdown spectroscopy.

[8] Verra is a nonprofit organization that operates standards in environmental and social markets, including some of the world's leading carbon crediting program.

8.4.3 Cultural Factors and Technification Challenges

Implementation of low-carbon practices in Brazilian agriculture also involves confronting skepticism and a somewhat conservative mentality amongst farmers and ranchers. Social and cultural factors influence farmers' behaviour, meaning that beyond exclusively technical challenges, social issues can be crucial in shaping low-carbon transitions (Bradford et al., 2019; Thamo & Pannell, 2016).

Increasing the level of carbon stocks in the soil helps to accumulate organic matter, which improves soil quality and plant development, and can lead to a virtuous circle of yield increases and improved profitability, combined with positive sustainability outcomes. Conversely, traditional modes of production often rely on outdated methods that compromise both outputs and sustainability but may remain deeply rooted amongst producers (Bungenstab, 2012).

Transforming the modes of production can imply challenges for producers, as this requires changes in the planning and improved knowledge of new production systems (Nobre & Oliveira, 2018). Moreover, the idea of carbon markets is very abstract to many producers, with a 2022 survey suggesting that 50% do not understand how the carbon market function and fear that the changes towards improved sustainability could compromise their outputs (Ferreira et al., 2022). Anecdotal evidence also suggests that farmers in Brazil fear that the definition of a carbon market framework by developed countries could lead to competitive advantages for their farmers. Behavioural change is, therefore, likely to hinge on the ability to demonstrate that decarbonization brings agronomic benefits, which often materialize in the long term. Property succession by younger generations can be important to accelerate the transition towards low-carbon agriculture in Brazil. Younger producers are generally more positively minded towards new technologies and sustainability issues. Yet, significant concerns remain, related to profitability, contractual obligations, credit access, and MRV costs (Thompson et al., 2022; Ritter & Treakle, 2020). Considering the high costs of transitioning towards more sustainable production models and implementing MRV systems, companies need to be transparent about this and make significant efforts of communication to earn farmers' trust.

Technical assistance, based on research efforts with replicable results, is also key to encouraging the spread of low-carbon practices. Agriculture is an extremely heterogeneous sector, marked by the co-existence of farms adopting cutting-edge practices, with other operations using extensive, low-productivity ones. For instance, although no-till is now widely adopted in Brazil, obtaining the full sustainability benefits of no-tilling requires a degree of technical capability beyond the reach of most farmers. Technical assistance is, therefore, crucial as it can support farmers' adoption of rotation between a greater variety of crops. The livestock sector provides another important example, given the enormous disparity amongst ranchers, which constitutes a group that both comprises producers who still rely on deforestation to expand low-yielding production areas, to others who make use of modern practices for pasture management, integration with crops and forestry, and feed supplementation with agricultural co-products.

Bragança et al. (2022) show that personalized training and technical assistance for Brazilian ranchers in sustainable pasture restoration provides long-term economic and environmental benefits. Producers in the Cerrado have thereby been able to raise productivity and their income by 39%, a model with potential for replication in the Amazon region. Ranchers trained for 2 years have increased outputs and profits and moreover obtained a reduction in GHG emissions through carbon sequestration and avoided emissions. Technical assistance is also crucial in the implementation of CLFi systems, due to the complexity of managing the interconnected components crops, livestock, and forestry within one single production system. Successful CLFi adoption can provide significant financial returns, as illustrated by the example of the *Santa Brígida* Farm, in Goiás. Prior to the implementation of CLFi, the farm operated with a loss of US$ 40/ha. However, after 14 years of transition, it produced a profit of US$ 1400/ha (Porto, 2021).

Hence, integrated or advanced no-till systems provide a path for productive transformations that permits reconciling economic and sustainability gains. Carbon credits generated through GHG mitigation could provide an additional incentive to pursue this course of action. Changing producers' mindsets by highlighting the many-folded potential gains from the implementation of more sustainable production practices, combined with the provision of the necessary technical assistance to do so, thereby also appears to be essential to spur the transition towards low-carbon agriculture.

8.4.4 Coordination Towards Low-Carbon Agriculture

The scalability of carbon mitigation initiatives is crucial to their economic viability within the Brazilian agricultural sector. Considering the elevated verification costs and complex certification process for emission reductions undertaken by individual farmers, the pooling of resources in common efforts to create large joint projects can help the decrease marginal costs of transitions towards low-carbon agriculture. Moreover, the pooled data from different monitoring areas would reduce relative uncertainties of the carbon budget. This, however, requires significant coordination efforts between a wide span of rural producers. This highlights the need for aggregators or agents with a centrally coordinating function and with knowledge of the market. Rural cooperatives and input companies thus stand in an important position to assume such a responsibility. Especially the former can become key in facilitating insertion within carbon markets and undertaking critical coordination activities. Approximately 1200 cooperatives with more than 1 million members exist in Brazil (OCB, 2022). Some are characterized by an extensive structure of technical assistance encompassing complex technical services. Their highly detailed database of cooperative members frequently includes georeferenced properties, satellite images, and other types of data. This facilitates the construction of an inventory of soil carbon stocks, legal reserve areas, and permanently protected native vegetation within farms. Cooperatives can thereby act as aggregators and coordinators of initiatives for the systematic implementation of low-carbon production practices.

Another key role regards the development and calibration of soil carbon dynamic models. Several initiatives are currently in different stages of development and adoption within Brazilian agriculture, advanced by different entities such as Embrapa, Instituto Brasileiro de Análises (IBRA), and different private companies. While some develop their own models, others work to adapt pre-conceived models to the soil and climatic conditions in Brazil. As already noted, model adaptation is dependent on databases with field information, and of enhanced digitalization practices to gather, organize, and analyse a large amount of data. The value of robust information systems as a product/service is thereby likely to grow in a situation of increased attention towards compliance with decarbonization commitments. The organization and coordination of new actor constellations are still ongoing in Brazil. However, there is a clear need to increase research funding, additionally to the concerted effort made by Brazilian representatives in international forums to inform and share crucial information regarding NCS conceptions developed in the context of tropical climatic conditions.

8.5 Conclusions

Implementation of low-carbon agricultural practices can play an important role as an instrument for deep decarbonization. The specific institutional and technical instruments applied should nonetheless strive towards being contextually sensitive, which also means that no "one size fits all" model exists. Therefore, it is crucial to provide accurate and context-specific criteria and measures for agriculture. Different tools are required to support decarbonization efforts due to the highly diverse structure of Brazilian agriculture, which ranges from smallholders to megafarm operations. In this situation, carbon markets might serve to attract funding and capital for more sustainable agriculture. It is nonetheless critical that the operational framework is based on scientific soundness, as well as the strict observance of the principles of integrity and robust MRV methodologies. If properly structured with these principles and goals in mind, carbon pricing could help support efforts to spur the growth of a bioeconomy in Brazil. Ideally, such initiatives should also encompass other measures that take proper account of biodiversity, water use, and local livelihoods. This could yield a wide array of important sustainability outcomes, regardless of potential monetization via the carbon pricing mechanisms.

Radical decoupling of agricultural and livestock production from deforestation, by far the largest source of Brazilian GHG emissions, is also a critical condition to provide credibility around sectorial mitigation projects. This would permit Brazil to translate its comparative advantages in NCS into a strong position within future low-carbon economies. It is nonetheless important that the excitement for mitigating global warming from NCS is not used as an excuse to reduce the pressure to rapidly reduce fossil fuel consumption. The market for NCS should serve to spur the adoption of technological innovations aiming to ensure climate mitigation and potential co-benefits in project regions, and not for the purpose of permitting the perpetuation of archaic energy systems by large global emitters.

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