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RESEARCH ARTICLE

Carbon farming initiative: a national-scale public-private partnership to promote regenerative agriculture in Brazil

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Summary

Climate change (CC) challenges food and climate through reduced crop yields and increasing production risk. Regenerative agriculture (RA) emerged as a pivotal strategy for enhancing crop productivity and soil organic carbon (SOC) sequestration, contributing to agriculture's CC mitigation and resilience. Nevertheless, expanding RA's main challenges is providing sufficient science-based decision support for farmers and other stakeholders. In this context, we present herein the largest public-private partnership in Brazil to conduct research in a multidisciplinary collaborative scientific network on RA and describe the Carbon Farming Program approaches. Bayer SA leads the initiative, which also includes 11 partner institutions (*i.e.,* Universities, Research Institutions and Foundations, and Farmers organisations). The programme aims to assess the benefits of improvement of cropland management, intensified and biodiverse crop rotation plans on SOC, soil health, crop productivity, and profitability in a no-till system. The programme has a multi-scale approach with three main steps ('Research Partners', 'On-Farm Research Sites', and 'Carbon Program at Scale'). In total, it encompasses 1,906 farmers and 232 000 hectares across the Brazilian edaphoclimatic conditions. The programme has gathered a large database, integrating SOC and fertility determinations, and crop yields, to derive a quantitative evaluation of the impacts of sustainable agricultural land management practices adoption. Moreover, the programme enabled breaking through the gap of quantitative knowledge for the development of a novel mathematical model to predict SOC dynamics for tropical agroecosystems. This is worth supporting assertive decisions along the specific planning to promote scalability in the insertion of Brazilian agriculture in the global C market.

Keywords: sustainable agriculture; food security; crop productivity; soil organic carbon; cover crops; climate changes; scalability

Introduction

The impact of climate change, especially the increase in global temperature, has been associated with adverse effects on crop yields (Zhao *et al.*, 2017; IPCC, 2022). Moreover, the combination of population growth and changes in land use is expected to challenge food security (Molotoks *et al.*, 2021). The expected increase in global food demand is projected from 35% to 60% in the

2010–2050 period (van Dijk *et al.*, 2021). In this scenario, increasing crop yields, reducing greenhouse gas (GHG) emissions, sequestering atmospheric CO_2, and storing its C as soil organic carbon (SOC) become fundamental to ensuring food and climate security worldwide, thus posing an urging demand to integrate sustainable technologies in agriculture (Horton *et al.*, 2021).

Food systems, including its full value chain (farm inputs, land use change, transportation, food processing, storage, packaging, etc.) involved in feeding humanity, were responsible for emitting 18 Gt of CO_2 equivalent year^{-1} (CO_2e yr^{-1}) between 1990 and 2015, which represents 34% of total GHG emissions worldwide (Crippa *et al.*, 2021). Approximately one-third of the food-systems emissions (or 5.7 Gt CO_2e yr^{-1}) are generated by land use and land-use change (LULUC), which corresponds to almost 11% of total GHG emissions (Crippa *et al.*, 2021). Globally, LULUC were responsible for a cumulative loss of 133 Gt of C (487 Gt CO_2) in 12 000 years, with abrupt losses in the last 200 years, especially because of deforestation, poor cropland management, and degraded pasture (Sanderman *et al.*, 2017).

Among the main strategies to increase soil carbon sequestration and reduce GHG emissions, natural climate solutions (also called nature-based solutions – NBS) stand out for their mitigation potential of 23.8 Gt CO_2e yr^{-1} (Griscom *et al.*, 2017). In the next three decades (2020–2050), Brazil is the country with the highest NBS mitigation potential (Roe *et al.*, 2019), with over 2.7 Gt CO_2e yr^{-1} (Griscom *et al.*, 2020). Given Brazil's role in the global food production scenario and the importance of carbon sequestration in the soils, which represents 25% of the global potential of NBS (Bossio *et al.*, 2020), the adoption of climate-smart agriculture is one way to contribute to climate change mitigation through SOC sequestration (Paustian *et al.*, 2016; Oliveira *et al.*, 2023).

The benefits of no-till and cover crops to improve soil ecosystem services and increase SOC stocks are widely known (*e.g.,* Jian *et al.*, 2020; Nicoloso and Rice, 2021; Maia *et al.*, 2022; Semmartin *et al.*, 2023). However, their potential to mitigate climate change varies considerably according to management practices, climate conditions, and soil attributes (Ogle *et al.*, 2019; Blanco-Canqui, 2022; Oliveira *et al.*, 2023). Furthermore, implementing effective large-scale soil-based climate change mitigation strategies requires a high capacity to measure, predict, and monitor emissions and removals in expanded observation networks and requires an integrated understanding of management practices, environmental drivers, and cultural, political, and socioeconomic contexts (Paustian *et al.*, 2016).

The challenge of producing more food with lower environmental impacts pressures for increasing crop yields so that demand could be met using the same or less land area. In such a scenario, adopting regenerative agriculture (RA) practices based on the pillars of ecological intensification has proven to be an essential strategy for improving resource use efficiency and reducing the environmental impacts of the agricultural sector, especially in tropical and subtropical regions (Geertsema *et al.*, 2016; Jhariya *et al.*, 2021). More intensified and biodiverse cropping systems can enhance crop yield, SOC and nitrogen (N) stock, biodiversity, the use efficiency of N, water, and radiation (Novelli *et al.*, 2017; Caviglia *et al.*, 2019; West *et al.*, 2020; Jones *et al.*, 2021; Semmartin *et al.*, 2023; Yang *et al.*, 2024; Souza *et al.*, 2024). Nevertheless, agronomic decisions to implement these RA practices require a deep understanding of the plant-soil system and several challenges need to be addressed. Among these challenges, we can highlight: (i) identifying and establishing high-biomass input cover crop species region-specific to ensure high crop yield combined with a high annual SOC sequestration rate; (ii) measuring and monitoring selected environmental and agronomic variables on a large territorial scale; and especially (iii) conducting research in a multidisciplinary collaborative network involving farmers, government agencies, and agri-food companies so that practices and policies are planned with due support and research is tested for performance and adoption in the field (Geertsema *et al.*, 2016; Paustian *et al.*, 2016; Isbell *et al.*, 2017; Jhariya *et al.*, 2021).

Carbon farming programmes begin to be designed and implemented around the world. For instance, the USA-based National Corn Growers Association supported the Soil Health Partnership, in which more than 200 farmers conducted trials in 9 states to compare conservation agriculture practices to typical management over 5 years of the programme (Wood and Bowman, 2021). In Europe, actions by the European Commission through 'Sustainable Carbon Cycles' have promoted carbon farming initiatives to encourage the agricultural and forestry sectors to adopt climate-friendly practices.

Given Brazil's leading position in agriculture and the data gap to support the development of scalable solutions to leverage the adoption of RA practices across the country, a nationwide public-private partnership covering 232 000 hectares has been established in 16 Brazilian states. Therefore, the objective of this paper is to present the scientific foundation and the main roadmap of this carbon farming programme, describing: (i) the main goals and challenges of introducing RA on a large scale; (ii) the approach of data foundation to establish the Carbon Farming Program in Brazil; and (iii) the main challenges and opportunities for expanding RA practices in Brazilian tropical and subtropical agriculture.

Carbon farming programme

The adoption of RA practices based on ecological intensification aims (1) to ensure the sustainability of agricultural systems, (2) to maximise the use of resources and inputs, and (3) to increase crop yields and economic returns, resulting in (4) environmentally friendly agricultural production systems (Tittonell, 2014; Jhariya *et al.*, 2021) (Fig. 1). Thus, RA seeks to ensure and improve soil health, increase SOC sequestration, improve the soil's physical quality and enhance biodiversity, regenerate the system, reduce externalities, and improve the ecosystem (Schreefel *et al.*, 2020). Adopting practices such as no-till, crop rotation and diversification, and the use of cover crops in the off-season can result in multiple benefits, such as (i) higher biodiversity, favouring the growth of the population of natural predators and weed control (Kocira *et al.*, 2020); (ii) enhanced nutrient cycling (Fernandez *et al.*, 2016); (iii) higher soil water availability (Basche *et al.*, 2016); and (iv) increased the C inputs to the soil (Semmartin *et al.*, 2023). Those aspects are the foundation to enhance soil health and make the system more efficient and less dependent on external inputs. In addition to sustaining higher crop yields and economic returns, the RA becomes a strategy to increase SOC sequestration and reduce GHG emissions (Yang *et al.*, 2024).

These diverse benefits of RA also face several technical challenges that need to be addressed to ensure the effectiveness and scalability of management practices. For instance, it is imperative to define the species used in the diversification plan considering the edaphoclimatic conditions of each region, cropping system, and the investment capacity of the farmer. Furthermore, there is not a clear roadmap for implementing these management practices on a large scale for a continental country such as Brazil. Another challenge involves measuring and monitoring several environmental (*e.g.,* SOC stocks, GHG emissions, weather variables) and agronomic (*e.g.,* cash crop yield, cover crop biomass production, economic returns) variables in a multidisciplinary collaborative network. In addition to the technical challenges, there are cultural challenges to adopting RA practices, since their benefits are mostly observed in the medium to long term. Thus, it is important to transfer the available knowledge to farmers and keep them engaged in good management practices and thereby obtain the benefits of adopting RA (*i.e.,* increased food production, maintenance of ecosystem services, and mitigation of the effects of climate change).

To overcome these challenges, a Carbon Farming Program was established in 2020 in Brazil and is constituted by a multidisciplinary collaborative network to test the impact of RA from a few experimental stations to 1906 farmers across the country, on the soil C sequestration, GHG emissions, soil health, and crop yield. This initiative is one of the largest public-private partnerships in the agricultural sector, led by Bayer SA, and counts on the participation of researchers from six public universities ('Luiz de Queiroz' College of Agriculture – University of São Paulo; Federal University of Rio Grande do Sul; Federal University of São Carlos; Federal University of Minas Gerais; São Paulo State University 'Júlio de Mesquita Filho'; and State

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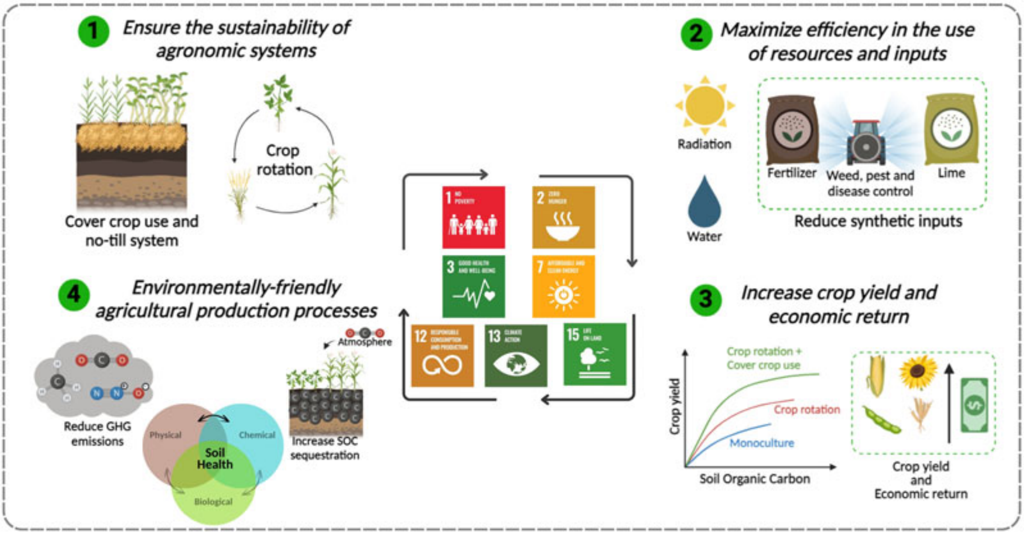

Figure 1. Regenerative agriculture (RA), based on the pillars of ecological intensification, advocates that the adoption of sustainable management practices is the action (1), increment of the system efficiency is the goal (2 and 3), and the agronomic and environmental benefits are the expected impacts of RA (4).

University of Ponta Grossa), two research foundations (Mato Grosso Foundation and ABC Foundation), the Brazilian Agricultural Research Corporation (Embrapa), the Center for Carbon Research in Tropical Agriculture (CCARBON), and the Brazilian No-Till System Federation. In total, the initiative involves 32 researchers, 30 graduate students (Master's and PhD) and post-doctoral fellows, 69 consultancies, and 1906 farmers. This large collaborative network is fundamental to establishing a triple helix model connecting field, market, and science. To create a reliable, transparent, scalable, and economically viable large-scale carbon programme, these three pillars must work together.

The Carbon Farming Program is composed of three main steps ('Research Partners', 'On-Farm Research Sites', and 'Carbon Program at Scale'), which are inter-related and encompass more complex controlled field experimentation in universities and research institutions to broader and scalable adoption of RA practices by the farmers in more than 232 000 hectares across the country (Fig. 2). The goals of each step and their methodology implemented to frame monitored long-term achievements are described below.

'Research partners'

The first step of the programme, called 'Research Partners', consists of a total of 31 field experiments (Fig. 2). Five short-term trials (< 5 years duration) were established at experimental stations located in three important grain-producing regions of the country. There are also other 26 medium- (5–20 years duration) and long-term (> 20 years duration) experimental sites coordinated by researchers from public universities, research foundations, and Embrapa involved in the initiative (called 'Carbon Experts'). In this step, the goals were to test different options and models of RA (*i.e.,* crop rotation, cover crop mixes, integrated farming systems, etc.) for regions with contrasting soil, climate, and management conditions, and evaluate the impacts on C balance (*i.e.,* soil C sequestration and GHG emissions), crop yield, and economic returns.

All short-term field protocols had no-till as a baseline of soil management (*i.e.,* business as usual), and crop rotations were implemented at increasing levels of intensification (*i.e.,* growing more crops to the existing cropping systems), with and without cover crops (Fig. 3). The main

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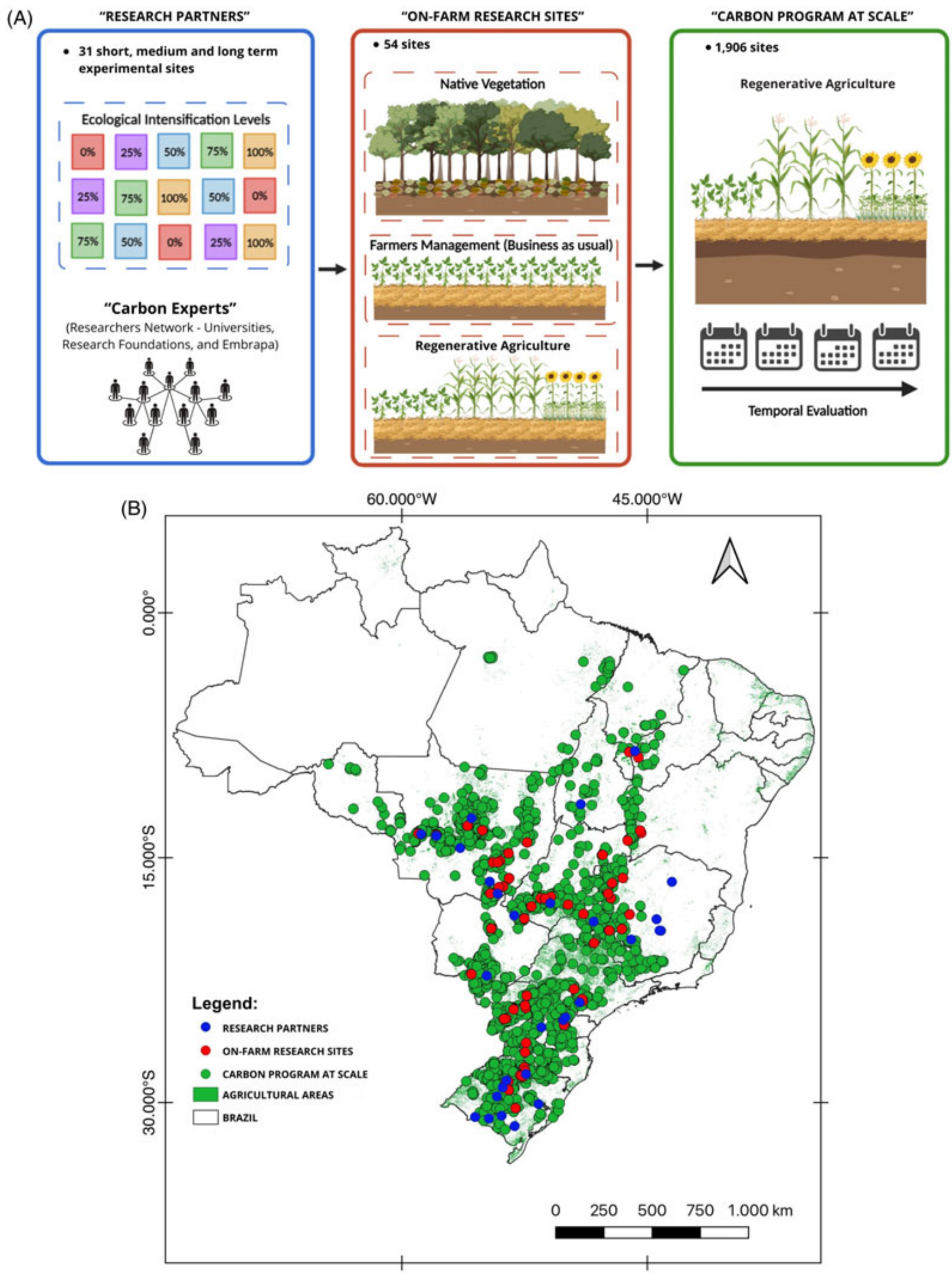

Figure 2. Three steps of the Carbon Farming Program in Brazil (A) and geographical distribution of the sites enrolled in this programme (B).

cash crops used in the protocols are soybeans, beans, maize, wheat, sunflower, and cotton. In addition, a wide range of cover crops are being used, especially from the Poaceae and Fabaceae families. Multiple agronomic and economic indices have been annually evaluated at these

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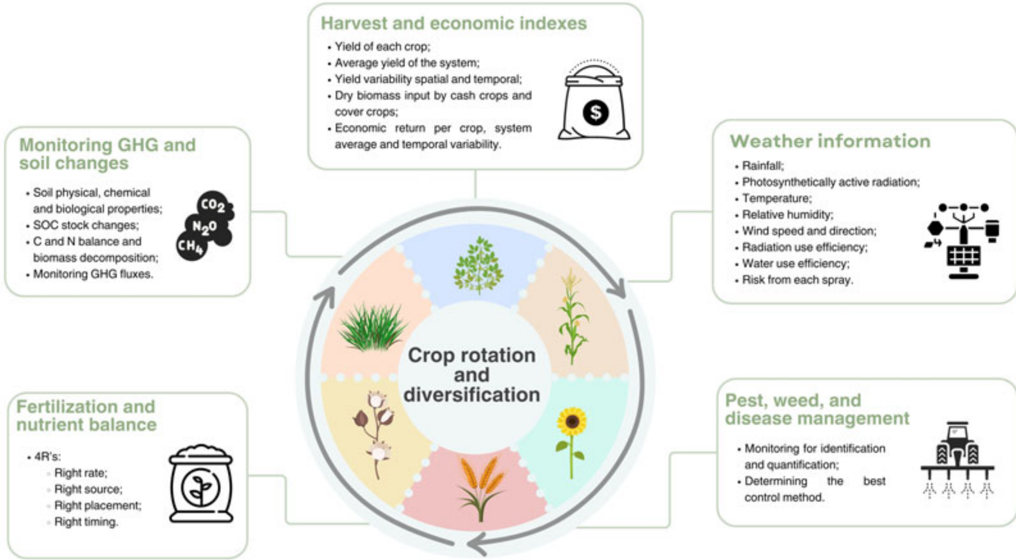

Figure 3. Field protocols assessed in the 'Research Partners' step.

experiments: (i) yield in kg ha^{-1} of each crop, (ii) average yield of the system expressed in energy (GJ ha^{-1}), (iii) yield variability spatial and temporal, (iv) dry biomass input by cash crop and cover crops, and (v) net income per crop. Weather information, such as rainfall, daily photosynthetically active radiation, temperature (average, minimum, and maximum), relative humidity, and wind speed and direction, has been collected to evaluate radiation and water use efficiency. The need to apply products to control weeds, pests, and diseases has been based on monitoring for their identification and quantification, enabling the determination of the best control methodology. As for the application of fertilisers, the apparent nutrient balance has also been used, seeking to optimise the use of inputs.

In short-term protocols, GHG emissions have been evaluate using static chambers, and soil parameters have been monitored up to 100 cm depth (*i.e.*, 0–5 cm; 5–10 cm; 10–20 cm; 20–30 cm; 30–40 cm; 40–60 cm; 60–80 cm; 80–100 cm). Soil physical (texture, soil density, aggregate stability, and penetration resistance), chemical (P, Ca, Mg, K, Al, H + Al, pH, and CEC), and biological (arylsulfatase and β-glycosidase enzyme activity, and carbon and nitrogen content) indicators have been evaluated. Carbon and nitrogen balances in the soil, SOC stock, and the annual rate of SOC sequestration (expressed in Mg ha^{-1} year^{-1}) are calculated from primary data. In medium- and long-term protocols, soil fertility, SOC, and crop yields have been monitored.

Through the evaluation of this set of environmental, agronomic, and economic parameters, it will be possible to identify the main management strategies and process technologies with the most significant effect on the increase of crop yield and reduction of environmental impact with a higher annual rate of SOC sequestration and lower GHG emissions.

'On-farm research sites'

The programme's second step is called 'On-Farm Research Sites' and consists of assessing at the farm level the results from the adoption of RA across a wide distribution of Brazilian territory. It allowed us to validate the 'Research Partners' layout within their regions of implementation, broadening the assessments in different edaphoclimatic conditions. With the main goal of monitoring changes in SOC stock, a focal group of 54 farms was selected to compare side-by-side fields (from 30 to 100 ha), where the management adopted by the farmers (soybean-fallow or soybean-maize rotation; business as usual) is compared with RA practices (*e.g.,* cash crop biodiversification and cover crops) implemented in the land management. In addition, a native vegetation area close to the fields was set as a reference sample (Fig. 2). A soil sampling protocol was developed to quantify the soil C stocks uniformly across the measured areas. To do so, soil samples have been taken annually since 2020 (as the baseline) to understand the variability of SOC and soil bulk density data and, consequently, the SOC stock. In total, more than 49 000 soil samples were collected, covering 8,320 hectares. Soil C content was evaluated by dry combustion using elemental analyzers (CHN). However, part of these samples were also analysed using spectroscopic techniques such as laser-induced breakdown spectroscopy (LIBS) and near-infrared diffuse reflectance spectroscopy to identify cheaper and faster alternative techniques. The database under construction is crucial for different purposes as to develop SOC dynamics predictive models regionally validated and coupled with intelligent algorithms. These models are being developed, calibrated, and validated for tropical climate conditions using an extensive monitoring network, which allows for greater reliability in predicting SOC dynamics (Campbell and Paustian, 2015; Noë *et al.*, 2023). Furthermore, these models may be used in measurement, monitoring, reporting, and verification activities and applied to projects in the carbon market, besides providing improved predictability on SOC stock outcomes of different projects. Furthermore, this database will help leverage the science development that can unlock unprecedented opportunities addressing the mission of the partnership in reducing the impact of climate change through RA.

'Carbon program at scale'

The third step of the programme called 'Carbon Program at Scale' consists of scaling up the adoption of the recommended practices of RA and involves 1,906 farmers covering 232 000 hectares under the wide soil diversification in subtropical (South) and tropical (further) regions of Brazil (Fig. 2). The main goal of this step is to promote the adoption of RA practices and monitor changes in SOC stock over time. For a cost-effective sampling protocol, the soil attributes have been monitored in the top-layer 30 cm (0–10 cm; 10–20 cm; 20–30 cm) as recommended by IPCC (2019). The first soil sampling campaign was conducted in 2021 to establish the baseline, resulting in almost 70 000 soil samples. The soil resampling was conducted in 2024 to calculate the SOC changes and, consequently, the SOC change rate (Mg ha^{-1} yr^{-1}) associated with land management monitored during this period. Moreover, the programme also aims to resample every three years to monitor changes in the SOC. The relevant distribution of farmers within this programme across the Brazilian territory provides wide combinations of the main drivers of SOC accumulation, allowing for a description of cultural, technical, and market challenges for each region to be engaged in an RA implementation.

Activities and advances of the programme

- **Training and outreach** – The science-based knowledge has been transferred to consultants, farmers, and other stakeholders through technical-scientific events (Carbon Science Talks in 2022 and 2023; Pro-Carbon Connection – 5 sites in 2022; and Pro-Carbon Connection in the field – 15 events in 2023), presential and remote training for consultants and farmers, and publications of scientific papers (Carvalho *et al.*, 2023; Freitas *et al.*, 2023; Gonçalves *et al.*, 2024) and two editions of the book *Practical Guide to Cover Crops* (Cherubin *et al.*, 2022, 2024).
- **Management practices** – The definition of the best biodiverse crop rotation plan for the different edaphoclimatic conditions of Brazil's agricultural areas was established in the 'Research Partners' step, validated in the 'On-Farm Research Sites' step, and scaled up to 1,906 farms in the 'Carbon Program at Scale' step. The results of crop yields, nutrient and

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water use efficiency, and SOC stocks obtained in the early steps of the programme are being written up for submission as scientific papers.

- **SOC assessments** – Throughout the programme, soil sampling protocols were established for each step, seeking to establish the best logistics to make the evaluations scalable. The SOC content of almost 119 000 samples was quantified, and laboratory proficiency tests were carried out to ensure reliable analytical results. Based on the C stock results obtained in the 'Research Partners' and 'On-Farm Research Sites' steps, SOC sequestration rates have been calculated for the different levels of intensification, allowing us to estimate their carbon accumulation potential. From the programme's results, Gonçalves *et al.* (2024) showed that in Brazilian savannas, the SOC stock was higher in croplands than in native vegetation. These findings highlight the potential of RA practices in sequestering SOC. Furthermore, from the large volume of data collected in the field, pedotransfer functions have been developed to predict soil bulk density values, which contributes to obtaining SOC stock results more accurately and cost-effectively. A predictive model of SOC stocks applicable to tropical and subtropical climate conditions has also been developed, allowing the identification of the main drivers of SOC accumulation in Brazil's agricultural areas. Another important advance was the updating of Verra's 'Verified Carbon Standard-VCS' protocol (Milori *et al.*, 2011; Segnini *et al.*, 2014; Villas-Boas *et al.*, 2020; Verra, 2023), which included laser-induced breakdown spectroscopy (LIBS) and near-infrared spectroscopy (NIRS) techniques for SOC quantification assessments and use as approved analytical techniques for measurement to generate verified carbon units as assets through verified projects. Both techniques have been applied by the carbon farming programme since 2020, allowing the SOC content to be measured quickly and at a low cost.
- **Soil health assessment** – Throughout the programme, soil samples have also been analysed to quantify mainly SOC and some physical, chemical, and biological indicators. These indicators have been integrated to assess and map soil health in Brazilian agricultural areas under various edaphoclimatic conditions. Furthermore, a low-cost on-farm soil health assessment kit, called 'KIT SOHMA' (National Institute of Industrial Property – Process number BR 10 2024 015629 3), was developed, with rapid and simplified protocols, allowing farmers to assess soil health indicators in the field.

Final remarks: challenges and opportunities

A multidisciplinary collaborative public-private network established in Brazil, involving universities, research institutions, consultants, farmers, and agri-food companies, resulted in one of the largest carbon farming programmes in the world. Notably, this programme is grounded in scientific expertise, featuring the involvement of prominent soil and plant scientists from Brazil's leading universities and research institutions.

Along the Carbon Farming Program journey, it will be possible to identify the region-specific potential of the management practices adopted (*i.e.,* RA) to increase SOC stock and the annual rate of carbon sequestration. Given the substantial volume of data generated by the programme, there is an opportunity to devise a robust SOC stock predictive model tailored to carbon farming in tropical and subtropical agroecosystems, while taking into account the prevailing regional agricultural practices. Given the wide distribution of the programme's activities in Brazil, it has been possible to obtain data on average SOC content under the most diverse conditions of topography, soil groups, soil textures, historical land cover and agricultural land management activities, native vegetation type, climate zone, and annual precipitation. In addition, it will be possible to identify the potential of RA practices to generate ecosystem services or other types of incentives for farmers as C credits through soil sequestration.

We hope that the continuity of the activities of the broad collaborative network established in the programme will address the gap in medium- and long-term large-scale field experiments in Brazil. Finally, we anticipate that the science-based strategy adopted in this Carbon Farming Program to quantify the agronomic and environmental benefits of RA will be useful in designing future initiatives in other parts of the world.

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