CHAPTER 3

Information management

Databases, functionalities and metrics on the carbon balance in agricultural systems

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Introduction

Growing concerns about climate change and sustainable use of natural resources are creating demand for more evidence-base and rational decisions by governments, institutions and organizations responsible for production chains, and consumers themselves. This decision making process ultimately involves and impacts all of society.

Effective decision-making relies on access to relevant information. One characteristic of information is that it can be interpreted and understood, and it is consequently useful for reducing uncertainties when evaluating different alternatives, supporting the decision making process. It is produced by processing, structuring and interpreting data, which is the raw material for better decisions. The less uncertainty associated with the information, the more assertive the decision will be, and the greater the chances of achieving the established objectives. Some methods even make it possible to quantify the economic value of information by modeling the decision problem (Gruijter et al., 2016). In this way, effective management of information is fundamental to improve rational decision making processes, planning, and technological innovation.

This chapter examines how information management and associated solutions apply in efforts to mitigate and adapt agriculture to climate change, considering the carbon balance. Essential databases, functionalities of information management systems, and the relevant metrics for monitoring and evaluating the carbon balance in agricultural systems will be presented in order to provide a comprehensive overview for researchers, producers, and policy makers.

Context

Before looking into the development and application of quantitative methods for estimating and projecting the carbon balance and other sustainability metrics in rural activities, we must contextualize the interface between the different processes associated with plant and animal production and both emissions and removals of greenhouse gases (GHG) from the atmosphere. This context will identify how data, information, and knowledge can generate benefits for both farmers and society in the context of climate change.

Despite the increase in clean energy production, global energy generation is still very dependent on fossil fuels: natural gas, oil, and coal, which together accounted for approximately 77% of the energy production consumed worldwide in 2023 (Our World in Data, 2025). Carbon dioxide (CO_2) emissions from burning these fuels have also grown over the past decade.

In addition to its primary function of guaranteeing food security, agriculture plays an important role in the carbon and nitrogen cycles, which are directly associated with the planet's climate balance and can contribute to controlling climate change. Plants use solar energy through the process of photosynthesis, absorbing atmospheric CO_2 and combining it with water to produce carbohydrates (sugars) for growth, storing the carbon in their biomass (leaves, stems, roots, grains, and fruit) in various molecules such as lignin, cellulose, and starch. Plants also breathe and emit CO_2 to generate energy for their metabolic processes. The difference between the carbon flows generated by photosynthesis and respiration is called net primary productivity (NPP).

The death of plant biomass throughout or at the end of the crop cycle generates dead organic material (like straw, leaves, and roots). This organic material, sometimes called litter, can be deposited above ground level or directly into the soil profile (mainly via the roots), as well as by the roots of living plants through a process called root exudation. The decomposition of litter and organic matter in the soil by microorganisms such as fungi, archaea, and bacteria also generates CO_2 emissions into the atmosphere. The speed of this decomposition is influenced by factors such as temperature, humidity, and soil aeration (Bhattacharjya et al., 2024).

The rate of change in soil organic carbon (SOC) stocks is therefore determined mainly by carbon inflows via litter decomposition and organic fertilization, and by carbon outflows (losses) associated with SOC decomposition, erosion, and leaching. In soil management, intensive tillage practices like plowing and harrowing can increase the decomposition rates of organic matter by increasing aeration and breaking up soil aggregates. The increase in NPP, obtained through crop diversification in the agricultural cycle or the use of cover crops, as well as the reduction in SOC decomposition rates through less soil disturbance (such as in no-till systems) can lead to an increase in stocks of SOC, a carbon previously captured from the atmosphere in the form of CO_2.

SOC sequestration is recognized as an important nature-based solution for mitigating climate change. Stocks of carbon stored in the soil around the globe are estimated at approximately three times the carbon present in the atmosphere, which represents a huge opportunity to use the soil as a carbon sink. This solution also offers several concurrent benefits that include increasing the resilience of agricultural systems due to greater storage of water and nutrients for plants, contributing to food security and generating benefits for farmers. International initiatives like 4p1000 (Rumpel et al., 2020) and the mapping of Global Soil Organic Carbon Sequestration Potential (GSOCseq) by the Food and Agriculture Organization of the United Nations (FAO) (FAO, 2025) demonstrate growing international interest in carbon sequestration initiatives in agriculture to offset GHG emissions into the atmosphere.

Animal production systems involve other emissions and associated gases besides CO_2. Animals, especially ruminants such as cattle, sheep, and goats, produce methane (CH_4) during enteric fermentation. Animal waste (namely manure and urine) also goes through a process of decomposition, releasing methane (CH_4) and nitrous oxide (N_2O), both potent GHGs. Proper management of this waste through practices such as storage in lagoons, composting, or the use of biodigesters directly influences emissions reduction.

Still before the farm gate, the application of nitrogen fertilizers can also lead to the emission of N_2O, another potent greenhouse gas. Urea, a nitrogen fertilizer, also emits CO_2 during decomposition. Correctives such as lime generate CO_2 when added to the soil, as does the burning of pastures or crop residues, which generate not only CO_2 but other GHGs.

In addition to the direct causes that generate carbon emissions and removals within the rural establishment such as those listed above, there are also other causes associated with production chains, which are indirectly attributed to agricultural products. The most widely accepted and used approach to accounting for emissions and removals throughout the product chain is life cycle assessment (LCA), which is addressed in a specific chapter of this book. For example, the LCA can include emissions associated with the upstream chain, such as mining, industrial processes, and transport for the production of fertilizers and soil amendments; GHGs involved in the production of animal feed (on and off the farm); and offsetting of fossil fuel emissions associated with the addition of beef tallow to biodiesel. Changes in land use and the GHGs resulting from the conversion of natural vegetation for agricultural expansion (whether direct or indirect) are also part of LCA accounting. What is known as a carbon balance is usually a simplified approach to the LCA, which seeks to quantify the amount of GHGs emitted and removed, and observe how this distribution varies over time.

Many studies have been carried out to develop models for simulating emissions, removals, or sequestration of carbon in agriculture, in order to support strategies that support the planet's climate balance such as improving estimates of carbon stored in the soil, for example. Efficient methods that provide appropriate estimates can also improve the efficiency of use of direct measurements in the soil; this avoids manipulation via trenching and turning the soil, which not only requires major efforts but also alters the soil's natural state.

The carbon footprint is a measure that quantifies the impact of human activities on the environment, specifically in relation to GHG emissions. Adopting these models has helped measure the carbon footprint of farms, and they have become increasingly important for identifying prevention and improvement actions and meeting consumer and market demands for products with lower environmental impact. The models simulate activities based on the data provided, and produce information that aids decision making. This evolution is also the way forward for national inventories. In order to develop simulation models, or even to calibrate and validate them under national conditions, data sets are required to help understand the processes being simulated. The better the quality of the data used in the modeling, the more assertive the results obtained will be, allowing more accurate assessment of the carbon balance. For this reason, structuring robust, consistent, high-quality databases that incorporate primary data from various sources is the first step towards effective information management. Unfortunately, only limited data on emissions and carbon balance are available at this time, mainly because these findings come from long-term experiments requiring ten or more years of data.

Historically, Brazil has increased its agricultural production by expanding the land involved, a practice which has led to deforestation, biodiversity loss, and soil degradation, especially in the Cerrado and the Amazon biomes. Sustainable intensification has emerged as a viable alternative, since it permits increased productivity without the need to expand the cultivated area, reducing environmental impacts. Within this scenario, integrated crop-livestock-forestry (ICLF) systems are gaining prominence as an effective strategy for sustainable land use. As we face climate change, it is essential to develop low-carbon agriculture in order to mitigate GHG emissions from the agricultural sector. Brazil has made progress in this direction through public policies such as the Sectoral Plan for Adaptation to Climate Change and Low-Carbon Emissions in Agriculture and Livestock (ABC+ Plan) (Brazil, 2021) and the National Program for the Conversion of Degraded Pastures (PNCPD) (Brazil, 2023). However, the effectiveness of these policies depends on updated data on the adoption and expansion of sustainable production systems — information that is not currently available with the spatial and temporal scope and level of detail needed to adequately support decision making.

The impact of agriculture on the carbon cycle depends on the balance between carbon sequestered and carbon emitted, as well as carbon from the processes indirectly affected along the production chain or as a result of land use. Sustainable agricultural practices aim to maximize the increase in carbon stored in the soil and plant biomass while minimizing GHG emissions associated with this production chain and changes in land use.

Generating carbon balance data

In the digital environment, data is transformed into information through computer processing. Within the context of agriculture, generating information on carbon yields comparable indicators that are built on preestablished and widely accepted methods, protocols, and metrics. Development of methodologies to quantify GHG emissions and removals associated with agricultural activities, potential carbon sequestration in soil and biomass, and considerations about scope and indirect emissions is essential for a consistent view of the carbon balance of production systems.

There are various indicators, methods, and metrics related to carbon assessment, developed for different purposes by different institutions. Some of the most notable analyses within the context of agriculture and agroindustry include:

- National reports on **GHG emissions and removals** produced by each sector, which take into account the standards established by the International Panel on Climate Change (IPCC)[1], the main international body responsible for assessing climate change.
- The **carbon footprint** of products, estimated using LCA, according to the principles established in various International Organization for Standardization (ISO) standards, such as ISO 14040:2006, ISO 14044:2006, ISO 14045:2012, and ISO 14064-2:2019 - part 2 (International Organization for Standardization, 2006a, 2006b, 2012, 2019).

[1] Available at: https://www.ipcc.ch.

- **Mitigation projects** through carbon capture in soil and vegetation, with standards set by certifiers: independent entities that establish and manage rigorous standards for certification of projects in order to reduce or remove GHGs from the atmosphere (Verified Carbon Standard, 2020, 2024).
- Net Zero projects intended to **neutralize emissions**, with guidelines established by the Science Based Targets Initiative (SBTi).
- The FAO protocol for **measuring, monitoring, reporting, and verifying** organic carbon in the soil in agricultural landscapes (FAO, 2020).

Each of these analyses has specific demands for data, with different models and algorithms that comply with assumptions related to time (such as longitudinal or punctual data, and static or dynamic processing), geographical scales (plot, farm, project, company, or country), as well as scope considerations (like sectorization of emissions, upstream and downstream chains, and indirect emissions). National reporting of GHG emissions and removals is addressed in other chapters of this book, so here we provide examples of the role of data and processing algorithms in generating information on soil carbon dynamics in agriculture.

One major barrier to accounting and remuneration of regenerative agriculture practices involving soil organic carbon sequestration is the lack of measurement, reporting, and verification (MRV) systems adapted to the demands of the carbon market. These systems are essential for both national GHG inventories and mechanisms such as emissions trading. It is crucial to reduce errors and variations in the quantification of carbon stocks in order to attract investment and provide sufficient credibility to public policies.

Changes in soil carbon stocks, whether diachronic or synchronic, can be quantified by means of interspersed sampling over time in the same area. However, this quantification through successive sampling is sometimes costly and inaccurate, depending on how it is done and the context where it is applied. For this reason, models of carbon dynamics in the soil are fundamental tools for ensuring the economic efficiency, accuracy, and scalability of MRV processes, which are also known as measurement, monitoring, reporting, and verification (MMRV) processes in atmospheric carbon removal initiatives involving natural systems and agriculture. These models make it possible to predict, quantify, and validate carbon sequestration in the soil, and in many cases they are recognized by international certifiers, used alone or in conjunction with determinations from field sampling, as well as by bodies such as the FAO and in emissions and removals inventories submitted to the United Nations Framework Convention on Climate Change (UNFCCC). In this context, these models of soil carbon dynamics play a strategic role for countries that have major potential to mitigate their emissions through nature-based solutions, including carbon farming initiatives.

Until recently, soil carbon dynamics models were developed in temperate countries, as illustrated in Figure 3.1, which presents the models, the countries responsible for their creation, and their development timelines. Recently, in a public/private partnership with Bayer, Embrapa developed a new biogeochemical model that makes it possible to assess and project changes in organic carbon stocks in the soil while taking into account specific national characteristics.

The relationship between soil carbon dynamics models and databases involves several aspects. The first refers to the data needed for their development. At this stage, data is essential to validate the structure of the model (in other words, the functional shape of the group of equations that comprise it), as well as to establish the most appropriate value or distribution of values for these equations. This creates a major

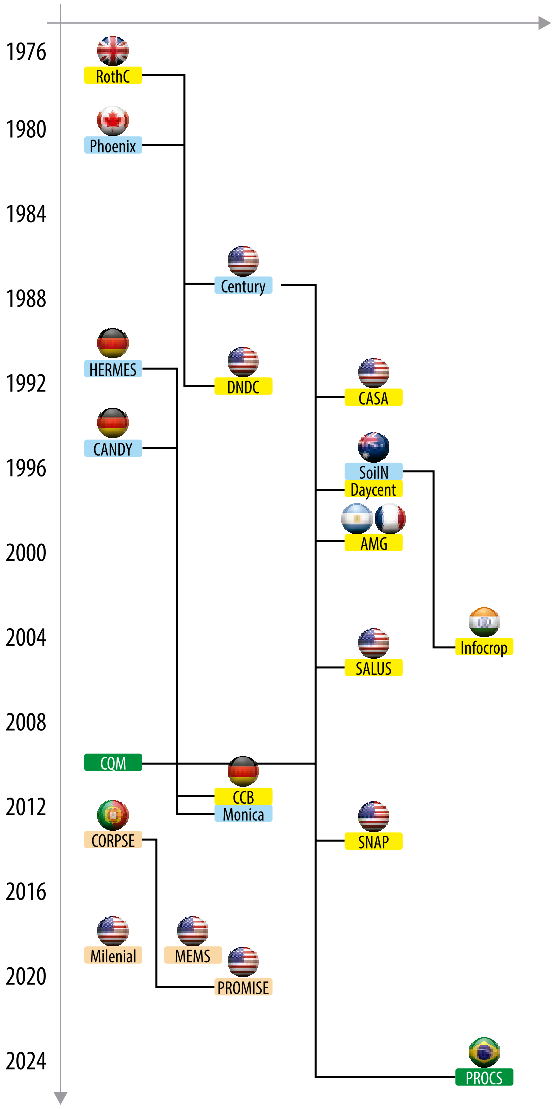

Figure 3.1. History, nationality, and origin of the main soil carbon dynamics models used worldwide.

Note: **Yellow**: multi-compartment models with non-measurable compartments that are being used for accounting in carbon market projects ("carbon farming"). **Blue**: multi-compartment models with non-measurable compartments that are not being used for accounting in carbon market projects ("carbon farming"). **Salmon pink**: multi-compartment models with measurable stocks. **Green**: mono-compartment models with continuous quality dynamics.

challenge in harmonizing the data in terms of units, making different methods of determination compatible, and dealing with time and space (including layer depth), among other attributes. The databases consequently must be organized, with robust and transparent procedures for harmonization and quality control. The second aspect is related to the data needed to evaluate the models. A model must be evaluated with independent data, in other words, data that was not used in the model's initial calibration process. It is also common to apply cross-validation procedures, where the original data set is divided into multiple partitions (known as folds) that make it possible to train and evaluate the model repeatedly with different combinations of these partitions. This process is used to estimate the model's performance on data that was not used during training, boosting its reliability.

Once developed, models need data. Data used in this context are known as inputs and can come from different sources, such as remote and proximal sensing, direct soil sampling with laboratory determination, automated machines such as grain harvesters, or data provided directly by the producer or extension worker. This data is also needed to evaluate or "validate" the model. In this sense, the comparison between the model's results and the measurements allows assessment of the model's suitability as a tool for representing the system by means of various accuracy and bias metrics. Considering that both models and measurements have their associated uncertainties, the validation of a model only indicates that data generated by the model or measured are not statistically different.

In dynamic models, field measurements can be used in conjunction with the trajectories estimated by the model, in order to improve the estimates compared to using either the model or measurements alone. This dynamic association between the model and data also allows the model to "learn" from the data by recalibrating its parameters in real time, resulting in better future projections. These procedures using data and models together to improve estimates of a variable's value and adjust parameters in real time (model learning) are commonly referred to as data assimilation, or model-data fusion. They have great potential to reduce monitoring costs and/or reduce estimation uncertainties. Model-data fusion also makes it possible to continuously recalibrate the model in real time for specific farms or plots, based on an assessment of the differences between the model's estimates and the observed data.

Carbon dynamics models can be incorporated into LCA tools, and more broadly, into MMRV systems that manage the monitored data, feed the model with data from different sources, run the model, and format the results for reporting and verification.

Eventually, when large quantities of data are available, it becomes possible to periodically carry out a generic recalibration of the model and integrate models with artificial intelligence tools. This fusion of models, data, and artificial intelligence has been called data learning.

Only with organized data and transparent procedures for management and processing (including the entire model development process) is it possible to achieve the credibility required to ensure the sustainability of public policies and incentives within the context of carbon.

The use of data associated with well-designed models makes it possible to develop policies and incentives, like creating carbon credit mechanisms that reward farmers for practices that sequester carbon or reduce emissions, as well as the development by public institutions of effective policies to mitigate climate change in the agricultural sector. In this sense, these institutions must provide the tools to monitor progress in reducing emissions and increasing carbon sequestration over time, supplying new means of accurately measuring and estimating these impacts. It is also important to understand the value of this information in order to create efficient, scalable, and impactful solutions. These new technologies undergo certification processes that guarantee the credibility of their claims to reduce emissions or sequester carbon.

Examples of models and methods developed by Embrapa using this data include:

- Methods for estimating soil carbon stocks using data assimilation;
- Functions for estimating soil density;
- Models for correcting carbon stocks (SOC/NIR) for decision making; and
- Models for estimating the value of information (VoI), considering the context of carbon credit markets.

Keeping in mind that this data is most often obtained and validated by different groups and under different circumstances, one major challenge is to organize the data into standardized bases to facilitate reuse and integration. Embrapa has been making strides in this direction. In the 2010s, the Fluxus, Pecus, and Saltus initiatives were launched, creating networks of researchers dedicated to the complex task of quantifying and understanding GHG emissions in grain, livestock, and forestry production systems, respectively. The data generated by these networks is being used to power various technologies covered in this book.

Embrapa's corporate data repositories

Over its 53 years of existence, Embrapa has been producing data and conducting research on the subject of GHGs and particularly carbon. This data goes through curation processes so it can be made available for reuse in new research, in the development of new methodologies, and in generating new knowledge and information. A data repository is an application or place where data is stored, organized, and managed for efficient access and use. Through such repositories, the data produced at Embrapa is available for access and use.

Solution 1 – Embrapa's Research Data Repository (REDAPE)

Embrapa's Research Data Repository (REDAPE)[2] is one of the company's corporate repositories for appropriate management of data throughout its life cycle, and permits the adoption of best practices in the stages of describing, preserving, publishing, and retrieving data collected as part of the company's research activities. Organized into nine major information domains, REDAPE contributes to the integration of data, information, and knowledge, facilitating data reuse by various stakeholders and promoting the transparency and reproducibility of the scientific process. In order to make this data available for access, it undergoes a curation process where the description of its metadata and the quality of the data itself are evaluated.

REDAPE stores various types of data from research; one highlight is data from carbon storage experiments, which are accessible to the company's researchers. Figure 3.2 illustrates the locations of long-term experiments with data stored in REDAPE, including those focused on carbon and research related to other parameters and indicators needed for carbon estimates. Note that in the region of the Federal District, where the Embrapa Cerrados research unit is located, 20 datasets from long-term experiments have been catalogued and are available.

Figure 3.3 shows the metadata description of one of the collections available in REDAPE, which includes data on pastures and carbon in livestock farming. In the example, we have data collected since 1996. With each new data campaign from this experimental area, a new dataset is deposited to form a collection of data from that research environment.

Anyone can consult the repository's data and metadata, which can also easily be found by artificial intelligence mechanisms. The

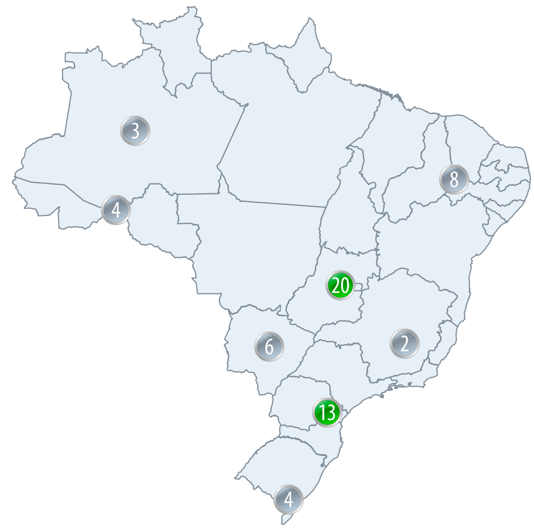

Figure 3.2. Locations of long-term experiments generating information on carbon and other indicators which is stored in REDAPE. The numbers indicate the number of experiments conducted in the region.

combination of this information and prospects for growth in the collection of data relevant to climate change helps to quantify the carbon balance, and improve the accuracy of national inventories of GHG emissions and removals.

Another example related to the carbon cycle is the integration of light detection and ranging (LiDAR) data and field forest inventories through a WebGIS (geographic information systems resource), which allows users to search for available data and their respective metadata, filtering them by date, location, and data type (Figure 3.4). Tropical forests store large amounts of carbon, and one of the most important parameters for studying the carbon balance in forests is above-ground biomass. Combining data from field forest inventories (which are expensive to obtain) with LiDAR metrics has proved effective in providing estimates of above-ground biomass in different forest formations (Longo et al., 2016). This type of data integration contributes to a better understanding of the role of forests in global sustainability at scales relevant to decision making, as well as in carbon emissions related to changes in land use, which also impacts decisions on food production.

[2] Available at: https://www.redape.dados.embrapa.br.

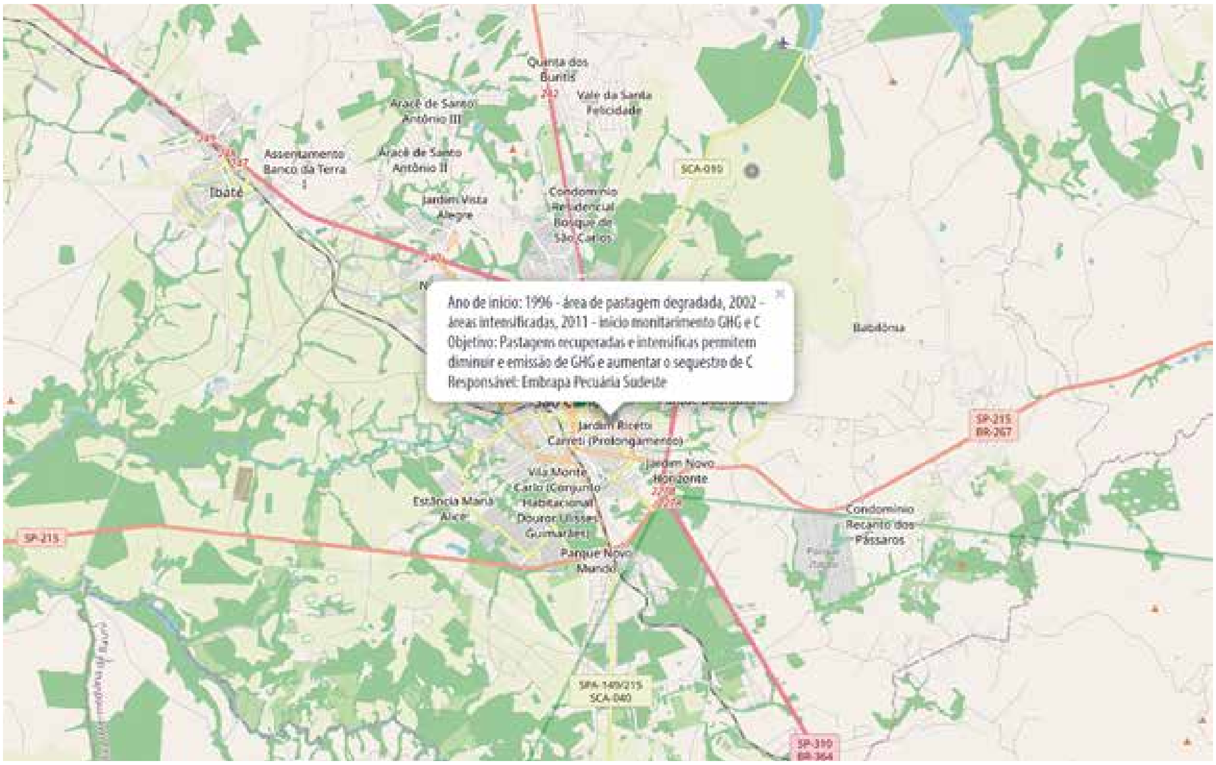

Figure 3.3. Metadata from one of the data collections on carbon available in REDAPE, referring to pastures used in research on carbon in livestock production. Text in the bubble indicates a starting year of 1996 with a degraded pasture, followed by intensified use in 2002 and the start of GHG and C monitoring in 2011.

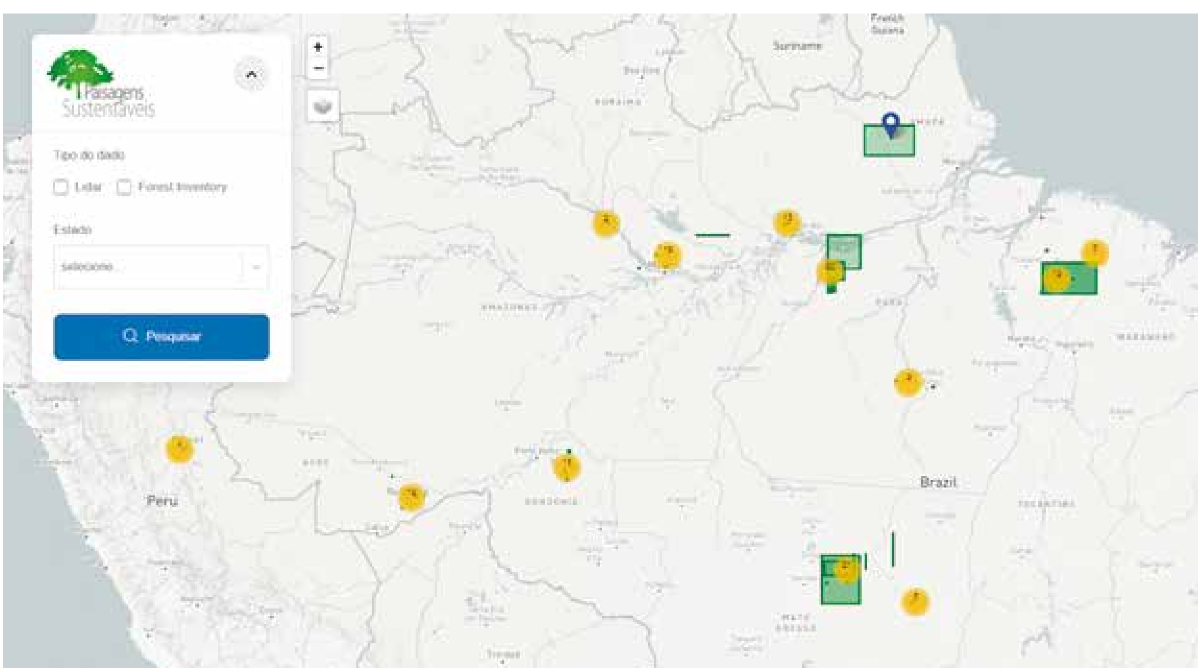

Figure 3.4. Map showing data from forest inventories and LiDAR surveys published in the REDAPE repository.

Source: Embrapa (2025d).

Solution 2 – Embrapa's spatial data repository (GEOINFO)

GEOINFO is another corporate repository for public access to maps and other spatial information produced by Embrapa. It contains around 1,500 maps in vector format (shapefiles), 500 maps in matrix format (raster), and another 900 documents including geospatial files for download, reports, and layouts for printing.

Many of these resources are organized into map sets for direct viewing on the platform, such as the set of maps depicting soil organic carbon stocks in Brazil, at spatial resolutions (pixel sizes) of 1 km (Figure 3.5) and 90 m (Figure 3.6).

Another map depicts soil carbon stocks on a state-level scale, released in 2025 for the state of Rio de Janeiro (Figure 3.7).

Also noteworthy are around 600 agroecological zoning studies for various agricultural crops in different regions, states, and municipalities, which are available for consultation and download on GEOINFO, as well as economic/ecological zoning studies and local studies for construction of underground dams, for example. Zoning studies analyze the environmental characteristics of a region and identify the most suitable locations for planting, which promotes appropriate and sustainable use of land and food security while preventing damage to society and the environment.

All the available maps are accompanied by metadata containing detailed information on authorship, use licensing, methodology used, the spatial reference of the map, and links to associated maps and documents. The contact details of the person responsible for the map are also available, so that the user can have direct access to the person who produced the data in case of any questions or requests.

Figure 3.5. Map depicting soil organic carbon stocks in Brazil, at 1 km spatial resolution.

Source: Embrapa (2025a).

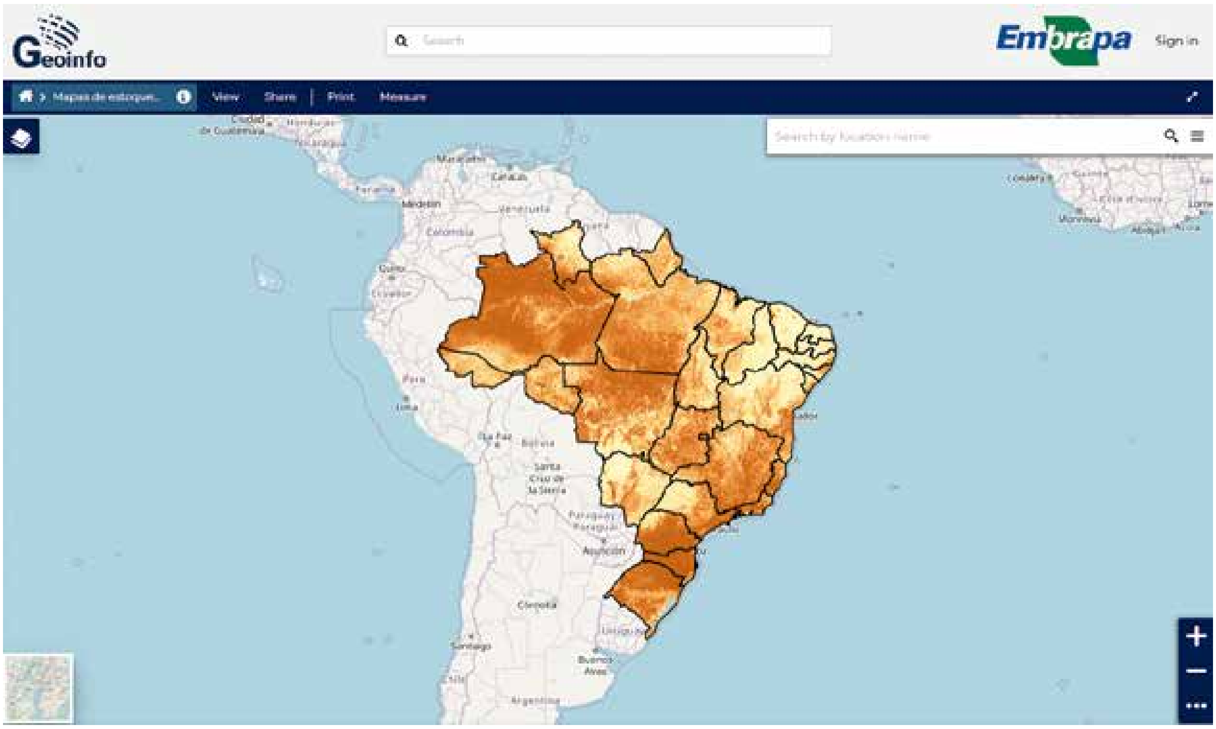

Figure 3.6. Map depicting soil organic carbon stocks in Brazil, at 90 m spatial resolution.

Source: Embrapa (2025b).

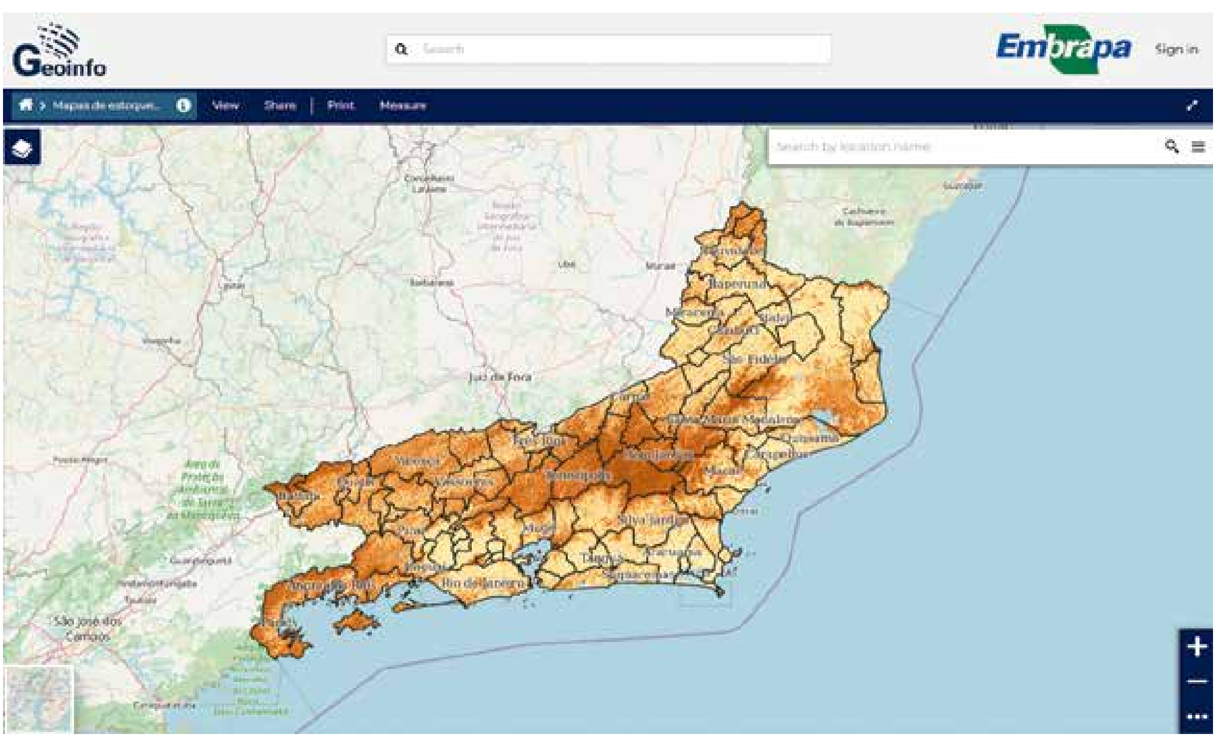

Figure 3.7. Map depicting soil carbon stocks in the state of Rio de Janeiro.

Source: Embrapa (2025c).

GEOINFO is linked to the Infraestrutura Nacional de Dados Espaciais (National Spatial Data Infrastructure) (INDE, 2025), which means that maps and other content can also be consulted through this platform. More experienced users can access the maps via geoservices for visualization (WMS) or manipulation of vector (WFS) or grid (WCS) data, and even access the metadata via an application programming interface (API).

Embrapa's Spatial Data Infrastructure can be accessed on the GEOINFO website,[3] where search, visualization, and content download tools are also available, along with various filters that permit more refined searches with filters like data type, keyword, author, date, and location, as illustrated in Figure 3.8. The collection of maps produced by Embrapa can also be accessed using the QR code in Figure 3.9.

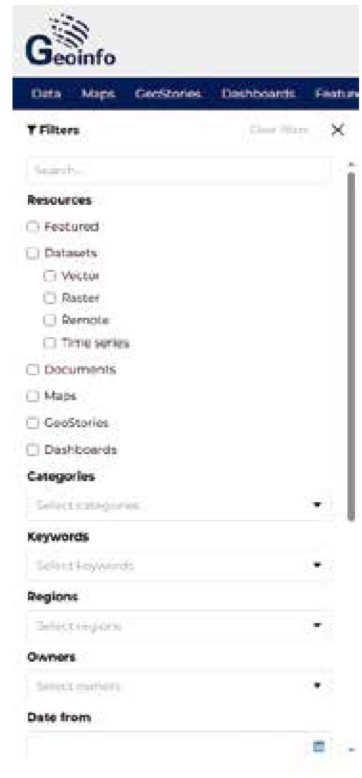

Figure 3.8. Some of the filters available in GEOINFO.

Source: Embrapa (2025e).

Figure 3.9. QR code to access GEOINFO.

Source: Embrapa (2025e).

Solution 3 – Embrapa's open-access institutional repositories (RIAAs)

Embrapa's open-access institutional repositories (*repositórios institucionais de acesso aberto*, or RIAAs), namely the Repositório Acesso Livre à Informação Científica da Embrapa (Repository for Open Access to Scientific Information of Embrapa,[4] ALICE) and the Repositório de Informação Tecnológica da Embrapa (Repository of Technological Information of Embrapa[5], INFOTECA-E), are intended to make Embrapa's technical and scientific publications widely available, with computer resources for searching, indexing, interoperability, and integration with other systems. The ALICE repository integrates scientific information produced by Embrapa and published in formats such as book chapters, articles in indexed journals, conference proceedings, theses and dissertations, and technical notes, while the INFOTECA-E repository provides information on technologies developed by Embrapa in the form of booklets, books for technology transfer, and radio and television programs. The language used in the radio and television content is adapted so that farmers, extension workers, agricultural technicians,

[3] Available at https://geoinfo.dados.embrapa.br.

[4] Available at www.alice.cnptia.embrapa.br.

[5] Available at www.infoteca.cnptia.embrapa.br.

students and teachers from rural schools, cooperatives, and other segments of agricultural production can assimilate the materials more easily and then use the technologies produced by Embrapa.

Both repositories allow users to search for terms in specific fields and within the full text of publications, making it easier to search for and retrieve documents. They also offer resources for obtaining content through open protocols and APIs, a resource widely used to promote interoperability between systems and platforms.

The over 185,000 publications available include a wide variety of content directly related to the carbon cycle, and comprise a corpus of high-quality, precise, and rich information. This makes it possible to produce answers based on facts from consolidated research. Figure 3.10 illustrates part of the search results for publications containing the term "Carbon" in their titles in the ALICE repository, illustrating the longevity of Embrapa's research on this topic.

Recently, the use of publications and texts from reliable repositories and platforms has gained importance for generative artificial intelligence (AI) models, such as ChatGPT, Gemini, and DeepSeek. When these models are used, certain options such as retrieval-augmented generation (RAG) can refer to the publications consulted, along with their web address.

Resultado 1-10 de 497.

Ano de publicação	Título	Autor(es)
1988	Carbonic anhydrase polymorphisms in Nellore, Canchim and in dairy crossbred cattle in Brazil.	PANEPUCCI, L.
1991	Carbon isotope discrimination as a means to evaluating drought resistance in barley, rice and cowpeas.	AUSTIN, R. B.; CRAUFURD, P. Q.; HALL, M. A.; ACEVEDO, E.; PINHEIRO, B. da S.; NGUCI, E. C. K.
1993	Carbon isotope discrimination and drought tolerance of upland rice.	PINHEIRO, B. da S.; AUSTIN, R. B.
1994	Temperature and glucose effects on soil organic carbon: CO2 evolved and decomposition rate.	VASCONCELLOS, C. A.
1995	Dynamics of soil carbon, nitrogen and microbial biomass in tropical agroecosystems.	VASCONCELLOS, C. A.; FRANCA, C. C. M.; MARRIEL, I. E.
1997	Carbon and nitrogen assimilating enzymes of maize hybrids representing seven eras of breeding.	PURCINO, A. A. C.; ARELLANO, C.; ATHWAL, G. S.; HUBER, S. C.
1998	Temperature effect on carbon biomass in soils from tropical and temperate regions.	VASCONCELLOS, C. A.
1998	Impact of Amazonian termite populations on the carbon cycle of natural and managed forest systems: respiration rates in different termite food guilds.	HANNE, C.; MARTIUS, C.; FORSTER, B.; GARCIA, M.
1998	Strategies to restore sustainability of shifting cultivation focusing on carbon and nutrient balances.	VIELHAUER, K.; SÁ, T. D. de A.; DENICH, M.; VLEK, P. L. G.
1999	Correlation of sorghum and soybean shoot dry matter weight with carbon and nitrogen assimilation enzymes.	BRESSAN, W.; SIQUEIRA, J. O.; VASCONCELLOS, C. A.; PURCINO, A. A. C.

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Figure 3.10. Part of search results in Embrapa publications using the term "Carbon."

Source: Embrapa (2025g).

Figure 3.11 illustrates one phase of Gemini's processing, in DeepResearch mode, for the query "*Quais os principais trabalhos da Embrapa sobre balanço de carbono em sistemas agrícolas*?" ("What are Embrapa's main works on carbon balance in agricultural systems?")

In this way, the ALICE and INFOTECA-E repositories can use Embrapa publications to train generative AI models that produce informative, accurate, and contextually relevant answers. This is a very important model for promoting the generation of new knowledge from reliable, peer-reviewed publications maintained by recognized institutions, which can then be used for a wide variety of applications, including those related to the issue of agricultural carbon.

The existence of high-quality and extensive temporal data is one of Embrapa's differentials for conducting research on carbon, making the company an essential partner in joint efforts with different national and international institutions working to carry out activities in this area.

Activities by Embrapa that provide data to support public policies

By providing tools for accurate and continuous monitoring, Embrapa makes direct contributions to land use planning and public policy management, as well as strategic agricultural planning, promoting a more efficient, resilient, and sustainable sector.

Solution 4 – The TerraClass project

The TerraClass project (Almeida et al., 2016) is a partnership between the Brazilian National Institute for Space Research (INPE) and Embrapa

Figure 3.11. One processing phase in Gemini, with references to the ALICE and INFOTECA-E repositories. The results contain projects in the areas of carbon metrics, integrated ICLF solutions, and low-carbon soy.

to systematically map land use and land cover in Brazilian biomes. The data generated in this systematic survey make it possible to monitor the impacts of the federal government's actions and public policies intended to develop and intensify agricultural activity as well as to preserve natural systems and expand understanding of land occupation processes. The survey generates official data on the dynamics of land use and land cover in the Amazon and Cerrado biomes, fundamentally expanding territorial management capacity and playing an essential role in understanding and monitoring the carbon cycle in Brazilian agriculture.

This work impacts the carbon cycle by mapping and qualifying land use and land cover in deforested areas, identifying whether the converted area can be now classified as pasture, agriculture (temporary, permanent, or semi-perennial), urban area, or secondary vegetation, for example. This information is vital for understanding land use transitions and consequently identifying the sources of carbon emissions resulting from land use change. The conversion of native forests into agriculture or pasture usually leads to a significant release of carbon stored in plant biomass and in the soil.

The project also monitors agricultural expansion over different types of vegetation cover. Understanding whether this expansion takes place in established pasture areas or over native vegetation is essential to assess the net impact on the carbon cycle. Expansion into native areas with potential for photosynthesis represents a loss of carbon sinks and becomes a source of emissions, while intensification of production into areas that have already been anthropized may have less of an environmental impact.

The project identifies processes of agricultural intensification, differentiating areas where a single crop is harvested from those that produce one crop as well as an off-season harvest. This distinction is important, since different agricultural practices can have different impacts on soil carbon sequestration and emission. Areas with more crops per year tend to have higher NPP, greater capacity to fix carbon in the soil, lower probability of erosion, and improved levels of biological activity and organic matter, among other advantages that increase carbon stocks in the soil.

TerraClass also monitors areas of secondary vegetation in different stages of regeneration, which play an important role in sequestering atmospheric carbon. Monitoring makes it possible to quantify the potential for GHG mitigation and climate change control through recovery of degraded areas.

The various data provided by this project support public policies such as:

- The ABC+ Plan for low-carbon agriculture, by helping to quantify the impact of the plan's different lines related to carbon sequestration and emissions reduction;
- Payments for Ecosystem Services (PES) and Reducing Emissions from Deforestation and Forest Degradation (REDD+), by providing accurate data, contributing to the credibility of these initiatives; and
- Territorial planning and environmental management, by identifying priority areas for conservation, sustainable agricultural expansion, and ecological restoration, considering the impacts on the carbon cycle.

The project's data is accessible through the WebGIS Portal, where it can be accessed in different formats. Figure 3.12 shows the portal, while Figure 3.13 demonstrates a feature that makes it possible to view changes in land use over time.

Although it is currently restricted to the Amazon and Cerrado biomes, TerraClass produces land use and land cover data for much of the country, including important agricultural centers. By providing reliable data that is updated every two years in the biomes with

Figure 3.12. TerraClass WebGIS Portal.

Fonte: TerraClass (2025).

Figure 3.13. Visualization of changes in land use over time in the Amazon biome.

Fonte: TerraClass (2025).

the greatest territorial dynamics, and using innovative methodologies, TerraClass has become an important tool for understanding the territorial dynamics of these regions in order to build more sustainable agriculture with less impact on the global carbon cycle.

Solution 5 – GeoABC+ technology solutions

Brazil occupies a leading position in world food production and exports, and accounts for a significant portion of the global supply of grains, meat, fibers, and agroindustrial products. This relevant profile as a major producer means that the country faces complex challenges, such as meeting growing global demand for agricultural products in a sustainable, transparent, and traceable manner within an increasingly demanding and competitive market and amid the context of climate change and its implications for food production and security (FAO, 2021).

Within this scenario, low-carbon agriculture has become an essential strategy for mitigating the GHGs generated by the sector. Recovery of degraded pastures and adoption of integrated agricultural production systems (like ICLF and agroforestry systems) are emerging as priorities, since they offer regenerative, low-carbon solutions with greater resilience to climate impacts.

The intensification of land use in national agriculture is a process that is increasingly present in the country's main agricultural regions, especially those linked to grain production, which have seen exponential expansion of double cropping systems (producing a main harvest as well as a second, smaller harvest in the same year) and adoption of ICLF systems, a process which has been recognized as the sustainable intensification of land use in Brazil (Silveira et al., 2022).

With this in mind, various players in national agribusiness (both public authorities and the private sector) have been promoting the adoption of ICLF systems as a technically appropriate strategy for making production systems more socially, economically, and agroenvironmentally sustainable. Some public policies in the sector that are in line with this perspective stand out, such as the Sectoral Plan for Adaptation to Climate Change and Low-Carbon Emissions in Agriculture and Livestock (ABC+ Plan) and the National Program for Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems (PNCPD) (Brasil, 2021; 2023).

In this context, it is imperative to invest in science, technology, and innovation (ST&I) as a central pillar for strengthening policies that target low-carbon agriculture — not just as a response to external pressures, but as a national strategy to ensure the sustainability and resilience of production systems, maintaining the country's competitiveness and leadership in the transition to more sustainable models of agricultural production.

In response to these challenges, Embrapa has led research, development and innovation (RD&I) efforts to develop technologies capable of providing data with true managerial and strategic value on the reality of national agriculture and the dynamics of land use in Brazil. In this way, the GeoABC+ technology solutions were developed through a partnership between Embrapa Soils and the State University of Rio de Janeiro (UERJ) to meet the demands of national agribusiness players — private companies, sectoral entities, and government bodies, in their planning and management processes (Simões, 2021).

The GeoABC+ solutions are a set of digital technologies which integrate AI with remote sensing to establish a monitoring system capable of mapping low-carbon agricultural production systems (such as ICLF) on an annual basis, generating essential data and information presented in the form of maps, spatial metrics, and indicators for expanding integrated production systems.

The GeoABC+ solutions (Kuchler et al., 2022) are based on the convergence of technologies applied as part of the following methodological steps:

- **Learning and validation database**: collecting and organizing field data referring to the history of production systems in georeferenced plots to train and validate AI algorithms, using machine learning and deep learning techniques.

- **Time series of satellite images**: obtaining and systematizing satellite data (spectral bands and vegetation indexes such as NDVI and EVI from various sensors including Sentinel2, Landsat, and Planet) which describe the phenological cycles of the various crops in consortium, succession, or rotation planting involved in ICLF systems.
- **Data cube**: creating matrix structures to store geospatial data extracted from satellite images, organized in multiple dimensions where variables, spectral bands, and vegetation indexes are referenced in space (latitude/longitude) and time (crop years).
- **Big Earth data**: applying techniques for analyzing large volumes of geospatial data.
- **Artificial intelligence**: application of machine learning and deep learning models (such as Random Forest, SVM, CNNs, etc.) to classify low-carbon production systems like ICLF.
- **High-performance processing**: use of parallel processing platforms in the cloud, such as Google Earth Engine.
- **Indicators**: extraction of metrics and indicators that describe the spatial distribution and expansion rates of production systems, in any territorial unit of analysis (states, municipalities, basins).

For example, Figures 3.14, 3.15, and 3.16 show results from the GeoABC+ solutions in the form of maps and graphs, with expansion indicators for the different modes of the soy production chain in the states of Mato Grosso, Mato Grosso do Sul, and Goiás during the 2010/2011 and 2021/2022 harvest years.

Integrated agricultural production systems are characterized by their potential to regenerate and maintain the productive capacity of the soil, boosting agroenvironmental and socioeconomic sustainability in production systems. Furthermore, because they are more resilient to climatic extremes, these systems reduce risks and boost adaptive capacity in national agriculture.

By promoting the adoption of low-carbon agricultural practices like ICLF, players in this industry are driving the consolidation of a more sustainable national agricultural sector. As part of this panorama, the GeoABC+ solutions add to these efforts by providing strategic data and information that permit more assertive decision making and more effective territorial management, minimizing vulnerabilities, increasing national competitiveness, and contributing to the sustainability of national agriculture.

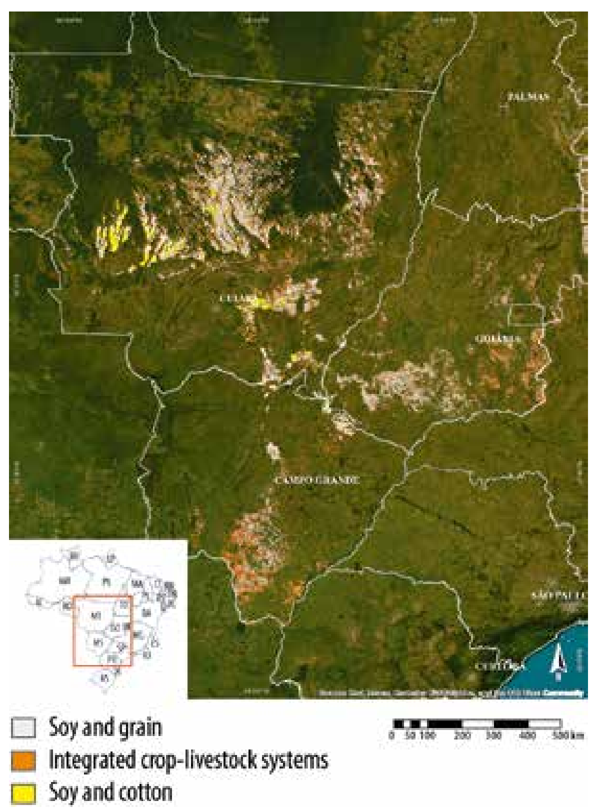

Figure 3.14. Spatial distribution of the different modes in the soybean chain for the states of Mato Grosso, Mato Grosso do Sul, and Goiás in the 2020/2021 harvest year.

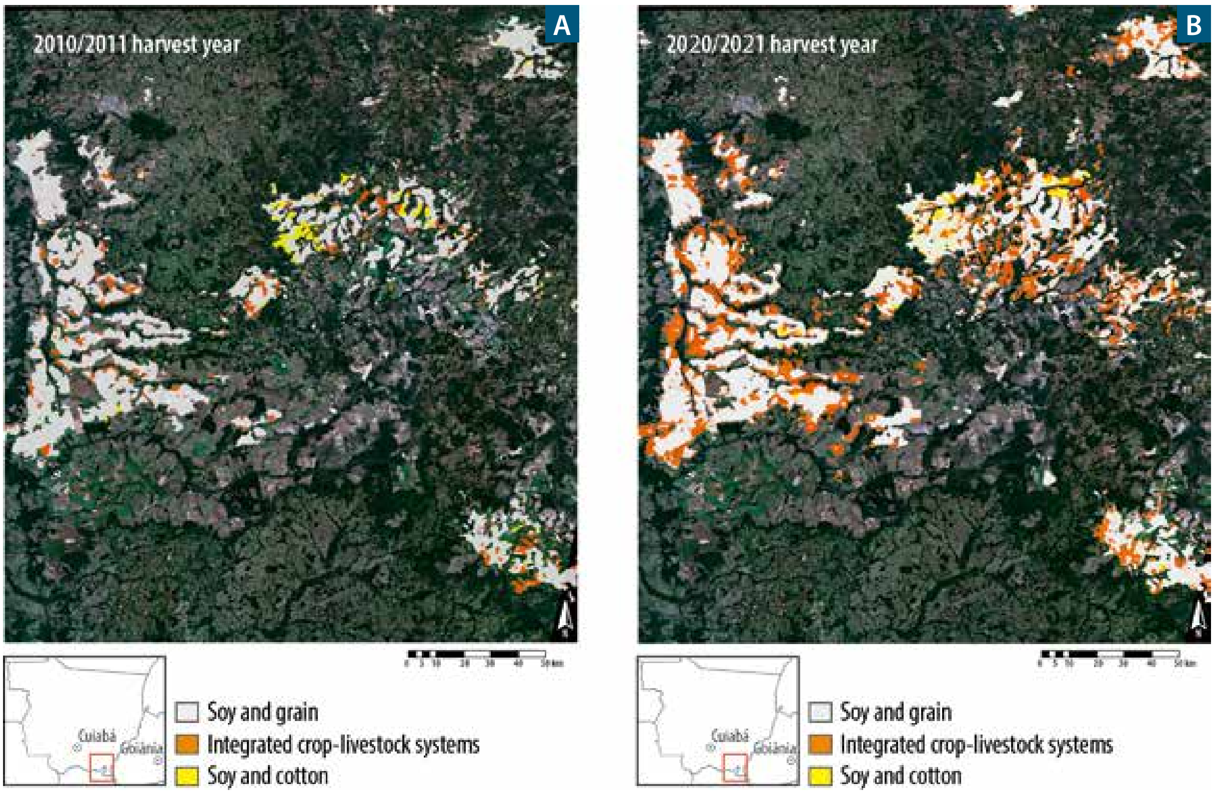

Figure 3.15. Detail (southern region of the state of Mato Grosso) of expansion in soybean modal systems for the 2010/2011(A) and 2020/2021(B) harvest years.

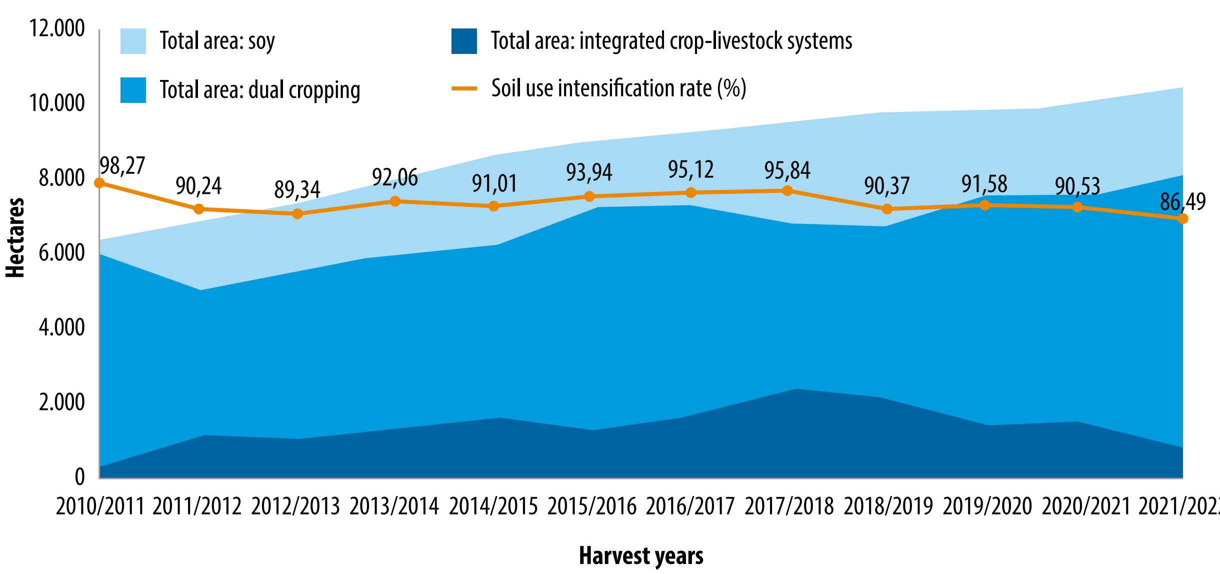

Figure 3.16. Expansion in area (ha) for the different modes in the soybean production chain in the state of Mato Grosso do Sul, 2010–2022.

Another important issue to highlight is the visibility that Brazilian agriculture can achieve through the dissemination of reliable data and indicators on expansion of low-carbon systems, which helps society more clearly understand the progress made by Brazilian agriculture towards sustainability.

The GeoABC+ solutions are based on constantly evolving technologies (such as AI, remote sensing, big data, and high-performance parallel computing), which means that the system must be updated continually. Advancement of these technologies will undoubtedly also permit progressive gains in precision, efficiency, and scalability for agricultural monitoring systems. Incorporating these innovations into GeoABC+ will make it possible to further expand the scope of the analysis, including detection of new agricultural production systems.

Finally, by providing strategic and qualified information, the GeoABC+ solutions help strengthen the competitiveness of Brazilian agriculture, solidifying the country's reputation as a leader in sustainable, low-carbon agricultural practices. The maps produced within the scope of this project are available on GEOINFO.

Solution 6 – Brazilian National Soil Survey and Interpretation Program (PronaSolos)

An initiative of the Ministry of Agriculture and Livestock, the Programa Nacional de Levantamento e Interpretação de Solos do Brasil (National Soil Survey and Interpretation Program, or PronaSolos[6]) aims to expand knowledge of Brazilian soils on a scale compatible with sustainable use and environmental preservation.

The Data Portal of the PronaSolos Technology Platform is a WebGIS environment for public access to soil map data and its technical interpretations, along with related topics, to support better territorial understanding. This visualization environment provides tools to manipulate and integrate spatial information for sustainable use of Brazilian soils. The portal currently has a large collection of studies on soils, different technical interpretations (such as carbon content and stocks in soils), and related environmental issues which are essential for understanding Brazil's territory and its sustainable use. Data is also available on political and administrative boundaries, river basins, biomes, geology, roadways and waterways, as well as query functionalities and spatial operations on the data in the database.

Contributions to national competitiveness

This technology provides a collection of data on Brazil's soils and their main characteristics, organized by topic and by format (vector or grid) to permit integrated visualization and use of the various operators available (spatial or non-spatial), with a focus on studies involving broad geographical scope. This organization allows the platform to provide the public with information plans that favor an integrated analysis of the territory and include data on planning units (like political and administrative divisions), enhancing this integrated analysis of Brazilian agriculture.

How to reduce exposure to risk and boost adaptive capacity

Studies of interpretative soil maps (such as those showing the agricultural suitability of land) and soil maps themselves provide information on carbon content, making them strategic tools for evaluating and promoting the sustainability of Brazilian agriculture. They offer a more accurate understanding of soil quality, carbon sequestration potential, and land use efficiency.

[6] Available at: https://pronasolos.sgb.gov.br.

The PronaSolos Data Portal[7] has a user-friendly interface that offers different tabs for selecting studies and tools for consulting and integrating data. Figures 3.17, 3.18, and 3.19 present the PronaSolos Platform, the map of available soil water in Brazil, and the map of available water and soil carbon content in Brazil.

This technology allows any citizen, public manager, teacher, or farmer to access this information, creating an environment of transparency and social empowerment. It also strengthens the use of maps as instruments of control for society, for example in the fight against illegal deforestation and occupation of vulnerable areas.

Impact on the sustainability of food production in Brazil and worldwide

The technology for providing maps of soils and other environmental components (including terrain, climate, land use, and water resources) has a transformative role to play in the sustainability of food production, both in Brazil and around the world. It serves as a strategic foundation for smarter, more efficient, and environmentally responsible agricultural decisions.

Solution 7 – Renovamap, a geospatial analysis system to assess eligibility for the RenovaBio program

The Brazilian National Biofuels Policy (known as RenovaBio, Law 13,576/2017) (Brasil, 2017) promotes the reduction of GHG emissions by encouraging production and use of biofuels. This policy plays a crucial role in the agricultural carbon cycle, mainly by encouraging production of low-carbon biofuels, promoting sustainable agricultural practices, and impacting changes in land use. Its main objective is to reduce carbon intensity in the transport fuel grid, making biofuels more competitive than fossil fuels in terms of emissions. Agriculture, as a supplier of raw materials, is key to achieving this reduction. RenovaBio recognizes and encourages the adoption of good agricultural and environmental practices, conservation of native vegetation, and use of waste, stimulating the adoption of production systems that minimize environmental impact and contribute to carbon sequestration.

Use of the LCA methodology to measure the carbon intensity of biofuels, from production of the agricultural raw material to use of the fuel ("from well to wheel"), encourages agricultural producers to adopt practices that reduce GHG emissions in their activities. At the same time, producers of efficient biofuels that are less carbon-intensive than their fossil counterparts generate decarbonization credits (CBIOS), which are financial assets that can be traded on the market. The lower the carbon intensity of the biofuel, the more CBIOs are generated per unit sold.

To ensure an effective reduction in emissions, it is essential that the raw material for biofuel production not be obtained from deforested areas or areas with a significant environmental impact. For this reason, specific criteria have been defined to guarantee appropriate use of the land by producers. In this context, Embrapa has developed and maintains Renovamap, a geospatial analysis platform for verifying producer compliance with the eligibility criteria. This tool offers functionalities so that Brazil's National Petroleum, Natural Gas and Biofuels Agency (ANP) can carry out these checks. In order to gain access to RenovaBio, producers must prove that:

- Their production does not come from deforested areas;
- Their property is registered and in good standing in the Rural Environmental Registry (CAR); and

[7] Available at: https://geoportal.sgb.gov.br/pronasolos.

Figure 3.17. The PronaSolos Platform.
Fonte: PronaSolos (2025).

Figure 3.18. Map of available soil water, obtained from the data portal.
Fonte: PronaSolos (2025).

Figure 3.19. Map of available soil water and carbon content, obtained from the data portal.

Fonte: PronaSolos (2025).

- Their operations are in compliance with applicable agroecological zoning (ZAE).

The system uses information from the CAR, satellite images, data from environmental monitoring programs, and mapping of consolidated production areas from the TerraClass, Prodes, and MapBiomas projects. Through geospatial analysis based on Sentinel images from 2018 to 2024 and generation of supporting documents, the objective is to verify the eligibility criteria for raw material producers, reducing costs and boosting transparency in the certification process for everyone involved in the chain.

Renovamap is a system that supports the RenovaBio policy, facilitating verification of areas and supporting monitoring. Based on public, consistent, and reliable data, this system provides individualized reports and cross-references mapping and satellite images for each property, providing information about eligibility that may need to be confirmed. Figure 3.20 depicts the reports generated by the system when evaluating a producer's eligibility. In the example, after running the assessment the system approved the producer, considering that the production area was not deforested, has active CAR registration, and is appropriate for oil palm production. Furthermore, the system displays a projection of the assessed area on images from public data, to facilitate visual analysis of the information.

Importantly, although RenovaBio's primary focus is not soil carbon sequestration, its guidelines and market mechanisms indirectly encourage agricultural practices that can lead to this additional benefit, while also promoting the production of biofuels with a lower climate impact.

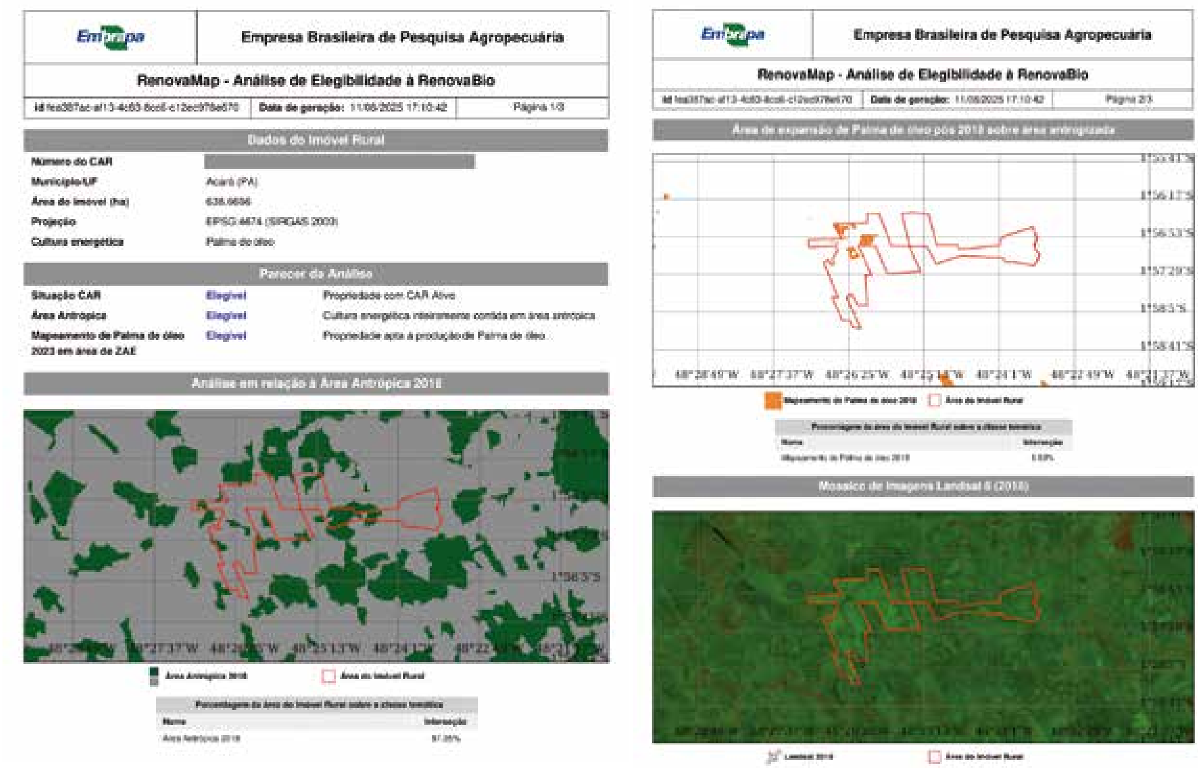

Figure 3.20. Report generated by the Renovamap System.

Source: Embrapa (2025f).

Examples of activities to mitigate greenhouse gases

Solution 8 – Milk's carbon footprint

Managing information on carbon footprint goes beyond simply managing research data. To guarantee the integrity, quality, and reliability of results, data collection and calculation methodology are fundamental.

Data collection is the starting point for quantifying the carbon footprint of milk. Brazil's enormous area, combined with six different biomes and cultural diversity, have resulted in heterogeneous production systems that are present in practically every municipality in the country, which makes data collection and standardization more complex. For the results to be valid and reliable, it is essential to obtain data in a systematic and rigorous manner, in order to avoid errors that could compromise the results and their subsequent analysis. Embrapa Dairy Cattle has been striving to ensure standardized and high-quality data collection to reduce uncertainties in results and ensure that more efficient practices and technologies based on scientific research are recommended. Assessment of data from roughly 2,000 dairy farms in different Brazilian regions and biomes made it possible to draw up a more comprehensive and accurate diagnosis of the carbon footprint for Brazilian milk (Paula et al., 2025).

Embrapa Dairy Cattle has used the LCA methodology recommended by ISO 14067 (International Standard Organization, 2018), which is globally recognized and widely adopted to quantify milk's carbon footprint.

This methodology guarantees credibility and comparability for the results related to this carbon footprint around the world. Using scientific research to determine the carbon footprint of milk not only strengthens the validity of the results, but also helps advance scientific knowledge, providing a solid foundation of accurate, well-structured data for new studies that will provide guidance and support for public policies and programs to reduce GHG emissions from milk production.

The construction of the Brazilian milk carbon footprint database demonstrates our commitment to sustainability, and to the millions of producers who make up the national dairy chain. By bringing together a solid scientific base, this bank of data makes it possible to quantify the impact of sustainable practices on reducing emissions, highlighting the potential of low-carbon dairy production. This initiative not only contributes to the mitigation of GHG emissions, but also strengthens the development of the sector and the country's food security.

The database represents a milestone for Brazilian dairy farming, with promising prospects for its advancement and consolidation. By covering detailed information on the characteristics of the different production systems (intensive, extensive, confined, and semi-confined) present in various regions of Brazil, this database offers a robust foundation for data validation, which is essential for low-carbon or zero-carbon milk certifications. This dataset can guide strategic actions at regional levels and by biome, strengthening traceability and credibility, which add value to the product in the domestic and foreign markets.

It is also a tool that can guide the implementation of mitigating practices and technologies; by identifying critical points and specific opportunities for each production system, the database supports public policies, encouraging the adoption of low-emission technologies and access to green credit lines. With continuous updates and partnerships with the private sector, Embrapa's database has the potential to position Brazil as a global benchmark in sustainable milk production, aligning productivity, competitiveness, and environmental responsibility. The first results and characteristics of this database can be seen in (Paula et al., 2025).

Solution 9 – Agricultural climate risk zoning (ZARC) database

One of the most critical risks that affect agricultural production is the occurrence of adverse agrometeorological conditions, especially drought, due to frequency and the significant loss potential (Arias et al., 2015). As one way of reducing the risk of adverse weather events, Embrapa partnered with the Ministry of Agriculture and Livestock (MAPA) to develop an agricultural climate risk zoning tool known as ZARC (Brasil, 2025). This agrometeorological study began in the late 1990s and has been subsequently refined, and identifies the most suitable sowing times for each Brazilian municipality. Zoning is done for different agricultural crops, taking into account each one's characteristics. A specially developed water balance model assesses water availability for the different crops, considering 36 sowing times throughout the year. Different crop cycle lengths (early, medium, late) and soil types are also taken into account (Santos; Martins, 2016; Steinmetz; Silva, 2017). This makes it possible to identify the sowing times with the lowest risk of adverse agrometeorological conditions throughout the crop's development cycle.

These zoning efforts require enormous quantities of all types of data, along with a significant computer infrastructure capable of carrying out a large number of simulations. As a result, Embrapa has been making efforts to ensure that the work is carried out swiftly, using the best data and information available. The main zoning datasets include: a) a meteorological data; b) data on agronomic characteristics of each crop; and c) data on soil characteristics.

The soil characteristics database contains information describing the physical and water properties of the country's different soil types, defining their water storage capacity. This information is relevant because soils with greater storage capacity allow agricultural crops to tolerate a longer period without rainfall, which has an impact on risk analysis. Originally, ZARC was based on three different soil types, but in 2021 a new database with information from 1,200 soil profiles was established and used to generate a new set of soil descriptions (Teixeira et al., 2021), with six classes of water availability (Monteiro et al., 2022).

The agronomic characteristics of the crops are used to adequately represent each crop when simulating agricultural risk. This database includes information such as the depth of roots and their ability to use the water present in the soil, the length of the crop's growth cycle and each of its phenological phases, as well as the rate at which the crop uses water in each of these phases. For each crop, ZARC usually considers three cycle lengths. All this information is obtained by Embrapa's crop specialists.

The largest database used in ZARC contains meteorological information, which must adequately represent the climate in the different regions of the country. This requires a large number of weather stations with a history of consistent data. The studies for ZARC, which Embrapa began in 2015, used data from over 3,500 stations from 1980 to 2013, obtained from different institutions such as Brazil's National Meteorological Institute (Inmet) and the National Water Agency (ANA). This database was analyzed thoroughly to remove outliers and provide a consistent source of information with good spatial representativeness. All the data was stored on Embrapa's servers in order to be readily available for use by the simulator.

The meteorological database used in the zoning studies has recently been updated, making the climate and risk estimates more representative. This new database comprises 4,128 stations, with data from 1993 to 2022, and uses information from ANA stations, Inmet and different state institutes, as well as data from remote sensing products or climate models like the Chirps database[8] and NASA Power.[9] Along with the station data, other specific databases for estimating extreme events (such as low or excessive temperatures and excessive rainfall) are used to calculate the risks for each planting season and Brazilian municipality.

The update to the weather database identified important changes in Brazil's productive regions, most notably a shortening of the period suitable for sowing, with significant impacts on the second crop in double cropping systems that produce two harvests each year.[10] Studies using the most recent data will allow us to identify the best sowing times while taking into account the climate changes that are already underway.

Embrapa has also conducted studies that consider future climate change scenarios using the Coupled Model Intercomparison Project Phase 6 (CMIP6) models. These efforts involve results from six global models, three emissions scenarios, and different global warming levels. All the models have undergone a bias correction process and are being used to assess the impacts of climate change on agricultural risk. The initial findings indicate a reduction in the low-risk window over a considerable expanse of Brazil's

8 Available at: https://www.chc.ucsb.edu/data/chirps.

9 Available at: https://power.larc.nasa.gov.

10 Bender et al. Trend analysis of the climate database used in the Agricultural Climate Risk Zoning (ZARC). Submitted for a special issue of the journal *Pesquisa Agropecuária Brasileira*, COP30.

territory, mainly affecting areas that utilize double cropping cultivation systems. This pattern is similar to the one identified when comparing the results from ZARC using the most current climate base (1993–2022) to the previous version (1980–2013). These findings suggest that the impacts of climate change on agricultural risks may already be underway today.

All these databases are integrated through the ZARC simulator, which assesses the risk for each of the 36 planting dates and considers the critical phenological phases of each crop. In this way, each zoning study involves simulations for the 4,128 weather stations that consider 36 planting dates, six soil classes, and three cycle lengths and result in over 2.6 million risk assessments. This huge number of analyses is only possible thanks to the computing infrastructure at Embrapa Digital Agriculture, as well as the data processing and visualization management tools developed specifically for ZARC by a team of dedicated developers.

Based on these databases (which are organized and maintained by Embrapa), and with the support of computer tools for simulating agroclimatic risk, ZARC provides important information on the most suitable times for planting. This solution[11] makes it possible to reduce the risks of agricultural activity, supporting farmers and rural insurance agents (public or private) and providing the scientific basis for studies into the impacts of climate change and adaptation strategies.

Future prospects

Against the backdrop of global climate change, low-carbon agriculture has become an essential strategy for mitigating the GHG generated by the sector. Within this context, recovery of degraded pastures and adoption of integrated agricultural production systems (such as ICLF and agroforestry systems) are emerging as priorities, since they offer regenerative, low-carbon solutions with greater resilience to climate impacts.

Along with boosting the competitiveness and resilience of the agricultural sector in the face of local and global initiatives to adapt to and mitigate climate change, it is also hoped that public policies and programs to encourage low-carbon agriculture will be strengthened. Because Brazil is considered one of the world's major grain suppliers, the country also has the potential to be a central player in mitigating emissions from agriculture and low-carbon livestock farming.

The growing demand for MMRV and carbon footprint indicators related to agriculture and its products is expected to generate a body of data with unprecedented range and quality control. Moreover, as mentioned above, construction of historical and current databases is essential to establish the potential sources and sinks of carbon and GHG in different compartments (plants, animals, and soil, for instance) within the agricultural sector. Nevertheless, Brazil does not yet have a collaborative, open-access platform for this purpose. Because of its regional diversity (which is expressed in aspects such as management practices, economic conditions, transportation logistics) and edaphoclimatic variations such as soil type, climate risk, and fragility of biomes, construction of a database to direct public policies must consider this conjectural variability. Managing these databases will give their owners a competitive advantage within the context of international negotiations and regulated markets, as well as when accessing more demanding export markets and voluntary carbon credit markets. There is a great global race underway to develop more precise quantification protocols that will make it possible

[11] Available at: https://mapa-indicadores.agricultura.gov.br/publico/extensions/Zarc/Zarc.html.

to refine estimates at a lower cost, with greater geographical generality and less dependence on specific inputs and practices. These demands have created challenges and opportunities across the entire spectrum of procedures associated with estimation, which include sampling techniques, remote and proximal sensing (satellite images), drones, vehicles with onboard sensors, probes, laboratory analysis, data quality control, modeling, simulation, optimization, new algorithms, as well as AI and data science applications and traceability. Advancement of these techniques is fundamental to support the carbon market in agriculture, making it possible to reduce uncertainties in project results.

The short-term expectation is that digital platforms will be developed which are capable of integrating production data, quality, and other elements of sustainability, in addition to carbon-related information. These tools will incorporate models, AI, and advanced data science techniques, and will be key elements for the success and competitive advantage of regenerative and low-carbon agriculture programs. Their role will be to ensure the proper integration of multidimensional data and support various processes involving quantification, data analysis, transparency, decision making, planning and auditing. These platforms are expected to evolve to also encompass other aspects of agricultural sustainability, such as water resources, soil health, and biodiversity.

References

ALMEIDA, C. A. de; COUTINHO, A. C.; ESQUERDO, J. C. D. M.; ADAMI, M.; VENTURIERI, A.; DINIZ, C. G.; DESSAY, N.; DURIEUX, L.; GOMES, A. R. High spatial resolution land use and land covermapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data. **Acta Amazonica**, v. 46, n. 3, p. 291-302, July/Sept. 2016. DOI: http://dx.doi.org/10.1590/1809-4392201505504.

ARIAS, D.; MENDES, P.; ABEL, P. **Revisão rápida e integrada da gestão de riscos agropecuários no Brasil**: caminhos para uma visão integrada. Brasília, DF: Banco Mundial, 2015. Available at: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1044224. Accessed: 21 May 2025.

BHATTACHARJYA, S.; SAHU, A.; SINGH, S.; SINGH, A. B. Factors affecting carbon sequestration and greenhouse gas emission in agroecosystems. In: MOHANTY, S. R.; KOLLAH, B. (ed.). **Greenhouse gas regulating microorganisms in soil ecosystems**. Cham: Springer, 2024. p. 107-126. DOI: https://doi.org/10.1007/978-3-031-70569-4_6.

BRASIL. Lei nº 11.815, de 5 de dezembro 2023. Institui o Programa Nacional de Conversão de Pastagens Degradadas em Sistemas de Produção Agropecuários e Florestais Sustentáveis e o seu Comitê Gestor Interministerial. **Diário Oficial da União**: seção 1, ano 161, n. 231, p. 18, 6 dez. 2023.

BRASIL. Lei nº 13.576, de 26 de dezembro 2017. Dispõe sobre a Política Nacional de Biocombustíveis (RenovaBio) e dá outras providências. **Diário Oficial da União**: seção 1, ano 154, n. 247, p. 4-5, 27 dez. 2017.

BRASIL. Ministério da Agricultura e Pecuária. **Plano ABC e ABC+**: Plano Setorial de Adaptação e Baixa Emissão de Carbono na Agropecuária – 2020-2030. Brasília, DF: Mapa, 2021. Available at: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/plano-abc. Accessed: 14 May 2025.

BRASIL. Ministério da Agricultura e Pecuária. **Programa Nacional de Zoneamento Agrícola de Risco Climático**. Brasília, DF: Mapa, 2025. Available at: https://www.gov.br/agricultura/pt-br/assuntos/riscos-seguro/programa-nacional-de-zoneamento-agricola-de-risco-climatico. Accessed: 23 jun. 2025.

EMBRAPA. **Geoinfo**. Available at: https://geoinfo.dados.embrapa.br/#/. Accessed: 14 May 2025e.

EMBRAPA. Mapas de estoque de carbono orgânico do solo do Brasil na resolução espacial de 1 km : Versão 2021 [CNPS]. **Geoinfo**. Available at: https://geoinfo.dados.embrapa.br/catalogue/#/map/4735. Accessed: 21 May 2025a.

EMBRAPA. Mapas de estoque de carbono orgânico do solo do Brasil na resolução espacial de 90 m : Versão 2021 [CNPS]. **Geoinfo**. Available at: https://geoinfo.dados.embrapa.br/catalogue/#/map/6700. Accessed: 21 May 2025b.

EMBRAPA. Mapas de estoque de carbono orgânico do solo do estado do Rio de Janeiro na resolução espacial de 30 m [CNPS]. **Geoinfo**. Available at: https://geoinfo.dados.embrapa.br/catalogue/#/map/6769. Accessed: 21 May 2025c.

EMBRAPA. **Paisagens sustentáveis**. Available at: https://www.paisagenslidar.cnptia.embrapa.br. Acesso: em: 21 May 2025d.

EMBRAPA. **RenovaMap**. Available at: https://www.renovamap.cnptia.embrapa.br. Accessed: 21 May 2025f.

EMBRAPA. **Repositório Alice**: acesso livre à informação científica da Embrapa. Available at: https://www.alice.cnptia.embrapa.br. Accessed: 21 May 2025g.

FAO. **Global Soil Sequestration potential (GSOCseq) map**. Rome, 2025. Available at: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/global-soil-organic-carbon-sequestration-potential-map-gsocseq/en/. Accessed: 11 jun. 2025.

FAO. **GSOC MRV protocol**: a protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes. Rome, 2020. DOI: https://doi.org/10.4060/cb0509en.

FAO. **The state of food and agriculture 2021**: making food systems more resilient to climate change. Rome, 2021. DOI: https://doi.org/10.4060/cb4476en.

GRUIJTER, J.J. de; MCBRATNEY, ALEX, B.; MINASNY, B.; WHEELER, I.; MALONE, B. P.; STOCKMANN, U.; Farm-Scale Soil Carbon Auditing. **Geoderma** v. 265, p. 120-130, Mar. 2016. DOI: https://doi.org/10.1016/j.geoderma.2015.11.010

INFRAESTRUTURA NACIONAL DE DADOS ESPACIAIS. **INDE**. 2025. Available at: https://inde.gov.br/. Accessed: 21 May 2025.

INTERNATIONAL STANDARD ORGANIZATION. **ISO 14040:2006**: environmental management: life cycle assessment: principles and framework. 2. ed. [S.l.], 2006a.

INTERNATIONAL STANDARD ORGANIZATION. **ISO 14044:2006**: environmental management: life cycle assessment: requirements and guidelines. 1. ed. [S.l.], 2006b.

INTERNATIONAL STANDARD ORGANIZATION. **ISO 14045:2012**: environmental management: eco-efficiency assessment of product systems: principles, requirements and guidelines. 1. ed. [S.l.], 2012.

INTERNATIONAL STANDARD ORGANIZATION. **ISO 14064:2019**: greenhouse gases: part 2: specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements. 2. ed. [S.l.], 2019.

INTERNATIONAL STANDARD ORGANIZATION. **ISO 14067:2018**: greenhouse gases: carbon footprint of products: requirements and guidelines for quantification. [S.l.], 2018.

KUCHLER, P. C.; SIMÕES, M.; FERRAZ, R. P. D.; ARVOR, D.; MACHADO, P. L. O. de A.; ROSA, M.; GAETANO, R.; BÉGUÉ, A. Monitoring complex integrated crop-livestock systems at regional scale in Brazil: a big earth observation data approach. **Remote Sensing**, v. 14, n. 7, 1648, Apr. 2022. DOI: https://doi.org/10.3390/rs14071648.

LONGO, M.; KELLER, M.; SANTOS, M. N. dos; LEITOLD, V.; PINAGÉ, E. R.; BACCINI, A.; SAATCHI, S.; NOGUEIRA, E. M.; BATISTELLA, M.; MORTON, D. C.. Aboveground biomass variability across intact and degraded forests in the Brazilian Amazon. **Global Biogeochemical Cycles**, v. 30, n. 11, p. 1639-1660, Nov. 2016. DOI: https://doi.org/10.1002/2016GB005465.

MONTEIRO, J. E. B. de A.; VICTORIA, D. de C.; FARIAS, J. R. B.; BARROS, A. H. C.; LIMA, E. de P.; ARAUJO FILHO, J. C. de; SILVA, F. A. M. da; EVANGELISTA, B. A.; TEIXEIRA, W. G. 2022. **Classes de água disponível do solo para uso no Zoneamento Agrícola de Risco Climático**. Campinas: Embrapa Agricultura Digital, 2022. 6 p. (Embrapa Agricultura Digital. Comunicado técnico, 135). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1144396/1/Com135-2022.pdf. Accessed: 21 May 2025.

OUR WORLD IN DATA. **Annual CO_2 emissions from oil**. Available at: https://ourworldindata.org/grapher/annual-co2-oil. Accessed: 21 May 2025.

PAULA, V. R. de; CARVALHO, B. C. de; MOREIRA, E. de A.; STOCK, L. A.; TONUCCI, R. G.; MIRANDA, T. de S.; TOMICH, T. R.; BENHAMI, V. M. L. **Pegada de carbono do leite brasileiro.** Juiz de Fora: Embrapa Gado de Leite, 2025. 9 p. (Embrapa Gado de Leite. Documentos, 293). ODS 2, ODS 12, ODS 13, ODS 15. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1174976/1/Pegada-de-carbono-do-leite-brasileiro.pdf. Accessed: 21 May 2025.

PRONASOLOS. **Programa Nacional de Solos do Brasil**. Available at: https://geoportal.sgb.gov.br/pronasolos/. Accessed: 21 May 2025.

RUMPEL, C.; AMIRASLANI, F.; CHENU, C.; GARCIA CARDENAS, M.; KAONGA, M.; KOUTIKA, L. S.; LADHA, J.; MADARI, B.; SHIRATO, Y.; SMITH, P.; SOUDI, B.; SOUSSANA, J. F.; WHITEHEAD, WOLLENBERG; E. The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. **Ambio**: a Journal of Environment and Society, v. 49, n.1, p. 350-360, Jan. 2020 DOI: https://doi.org/10.1007/s13280-019-01165-2

SANTOS, W. G. dos; MARTINS, J. I. F. O Zoneamento Agrícola de Risco Climático e sua contribuição à agricultura brasileira. **Revista de Política Agrícola**, ano 25, n. 3, p. 73-94, jul./ago./set. 2016. Available at: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/152623/1/O-zoneamento-agricola-de-risco-climatico.pdf. Accessed: 21 May 2025.

SILVEIRA, J. G. da; OLIVEIRA NETO, S. N. de; CANTO, A. C. B. do; LEITE, F. F. G. D.; CORDEIRO, F. R.; ASSAD, L. T.; SILVA, G. C. C.; MARQUES, R. de O.; DALARME, M. S. L.; FERREIRA, I. G. M.; CONCEIÇÃO, M. C. G. da; RODRIGUES, R. de A. R. Land use, land cover change and sustainable intensification of agriculture and livestock in the Amazon and the Atlantic Forest in Brazil. **Sustainability**, v. 14, n. 5, 2563, Mar. 2022. DOI: https://doi.org/10.3390/su14052563.

SIMÕES, M. G. **Monitoramento dos sistemas de integração lavoura-pecuária no estado do Mato Grosso do Sul a partir da metodologia GeoABC**. Rio de Janeiro: Embrapa Solos, 2021. Projeto finalizado.

STEINMETZ, S.; SILVA, S. C. da. **Início dos estudos sobre Zoneamento Agrícola de Risco Climático (ZARC) no Brasil**. Santo Antônio de Goiás: Embrapa Arroz e Feijão, 2017. 27 p. (Embrapa Arroz e Feijão. Documentos, 312). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1064577/1/CNPAF2017doc312.pdf. Accessed: 21 May 2025.

TEIXEIRA, W. G.; VICTORIA, D. de C.; BARROS, A. H. C.; LUMBRERAS, J. F.; ARAUJO FILHO, J. C.; SILVA, F. A. M. da; LIMA, E. de P.; BUENO FILHO, J. S. de S.; MONTEIRO, J. E. B.

de A. **Predição da água disponível no solo em função da granulometria para uso nas análises de risco no Zoneamento Agrícola de Risco Climático**. Rio de Janeiro: Embrapa Solos, 2021. (Embrapa Solos. Boletim de Pesquisa e Desenvolvimento, 272). Available at: http://ainfo.cnptia.embrapa.br/digital/bitstream/item/224270/1/CNPS-BPD-272-2021.epub. Accessed: 21 May 2025.

TERRACLASS. Available at: https://www.terraclass.gov.br/webgis. Accessed: 21 May 2025.

VERIFIED CARBON STANDARD. **VM0042**: improved agricultural land management: version 2.1: sectoral scope 14. [Washington, D.C.], 2024. VCS methodology. Available at: https://verra.org/wp-content/uploads/2024/09/VM0042v2.1_ImprovedALM_corrected_21Jan2025.pdf May 30, 2023. Accessed: 11 jun. 2025.

VERIFIED CARBON STANDARD. **VMD0053**: model calibration, validation, and uncertainty guidance for the methodology for improved agricultural land management projects: version 1.0: sectoral scope 14. [Washington, D.C.], 2020. VCS module. Available at: https://www.verra.org/wp-content/uploads/imported/methodologies/VMD0053_Model-Calibration-Validation-and-Uncertainty-Guidance-for-the-Methodology-for-Improved-Agricultural-Land-Management.pdf. Accessed: 11 jun. 2025.