

SCIENCE FOR CLIMATE

and solutions from Brazilian agriculture

**Strategies,
technologies
and indicators
for adaptation
to climate
change and
for greenhouse
gas emission
control
in tropical
agriculture**

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A close-up photograph of a hand holding a single, golden wheat stalk. The hand is positioned in the lower-left foreground, with fingers gently gripping the base of the grain. The wheat stalk is in sharp focus, showing the individual grains and the long, thin awns. The background is a soft, out-of-focus field of similar wheat stalks, creating a sense of depth and a warm, natural atmosphere. The overall color palette is dominated by warm, golden-yellow and light brown tones.

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Brazilian Agricultural Research Corporation
Ministry of Agriculture and Livestock

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Foreword

Humanity is experiencing a climate threat that challenges it to review its development models, production systems, and ways of occupying territories. Agriculture is at the heart of this challenge: it is one of the activities most vulnerable to climate impacts and, at the same time, one of the most decisive for building sustainable, inclusive, and effective solutions for national and global food security.

This book, published by Brazil's government during the COP30 (which the country has the honor of hosting in 2025), is a direct contribution from Brazilian agricultural research to tackling climate change. The result of collaborative work by researchers from the Brazilian Agricultural Research Corporation (Embrapa) and partner institutions all over Brazil, it systematically brings together an accessible and robust set of solutions, technologies, evidence, and metrics to support an effective transition to more resilient and low-carbon agri-food systems.

It also addresses priority issues for adaptation and mitigation in agriculture, with a focus on the specific characteristics of tropical and subtropical production. The content ranges widely, from the collection and organization of field data and development of national protocols and models to practical applications for quantifying greenhouse gas emissions and removals and adapting agricultural systems. It also proposes ways forward, based on gaps and successful experiences that have already been implemented.

Brazilian agriculture, which is present in all regions of the country, stands out for its diversity, quality, and food production capacity, in both family farming and large-scale production systems. Because this industry naturally depends on climatic conditions, it is simultaneously vulnerable and a protagonist, with a decisive role in the global climate and food agenda. This text demonstrates that we already have effective solutions to reduce emissions, conserve biomes, recover degraded areas, increase production efficiency, and adapt our systems to the new climate conditions. Technologies like integrated crop-livestock-forest systems, biological nitrogen

Photo: Saulo Coelho (Embrapa)





fixation, use of bio-inputs, precision agriculture, and agro-ecological systems are among the alternatives detailed in this book.

This knowledge extends beyond the limits of national production and strengthens what is known as climate diplomacy. By supporting national emissions inventories and compliance with the Nationally Determined Contributions (NDCs) and providing a foundation for Brazil's position in international negotiations on agriculture within the United Nations Framework Convention on Climate Change (UNFCCC), Embrapa is strengthening its position as a strategic reference in tropical science. Over five decades leading a robust agricultural innovation system, Embrapa has made decisive contributions to Brazil's transformation from a food importer into a global power in agri-food production. Its work has been essential in adapting international methodologies to the tropical reality, correcting distortions in global measurement models, and generating evidence-based data to reach consensus on climate justice.

The following pages also contain a vision of the country. Brazil maintains that the climate transition must be based on justice, international cooperation, and recognition of the positive contributions of agriculture in the Global South. The Brazilian experience, with its integrated production systems, robust public science, and active stance taken by farmers, shows that it is possible to expand productivity with less environmental impact and greater food security. This contribution is even more relevant given the alarming global data on food insecurity: in 2024, over 295 million people in 53 countries faced acute levels of hunger, an increase of nearly 14 million compared to 2023¹.

Besides bringing together solutions that can already be adopted, this publication strives to influence public policies and contribute to Brazil's international commitments as part of the Paris Agreement and the Conference of the Parties forums. Brazilian science has played an essential role in tropicalizing methodologies, advancing fairer metrics, and building scientific diplomacy that is respected around the world. This technically, strategically, and diplomatically

¹ 2025 GLOBAL report on food crises: joint analysis for better decisions. Rome, 2025. Disponível em: <https://www.fsplatform.org/report/global-report-food-crises-2025>. Accessed: 30 set. 2025.



valuable text is intended to expand adoption of sustainable practices and provide visibility for the role of tropical agriculture in addressing climate change.

The current reality on our planet highlights the urgent nature of coordinated actions to integrate food security and climate action. Solutions based on tropical science are one example of how knowledge can generate large-scale social, environmental, and economic impact. By proposing production systems that are more adapted to climate change and supported by robust metrics and technologies that are already available, Brazil is demonstrating that it is possible to produce more in a better way, while reducing emissions, conserving natural resources, and guaranteeing access to food. In this sense, Brazilian agricultural research and farmers are not only responding to global challenges but also leading an innovative and supportive response to the climate emergency and hunger.

These two globally relevant issues are the focus of at least two of the Sustainable Development Goals (SDGs) contained in the United Nations 2030 Agenda for Sustainable Development, which encourages action in crucial areas for humanity, namely People, Planet, Prosperity, Peace and Partnerships. Specifically on these topics, this book offers relevant contributions to SDGs 13 (“Take urgent action to combat climate change and its impacts”) and 2 (“End hunger, achieve food security and improved nutrition and promote sustainable agriculture”). It also contributes to SDG 12 (“Ensure sustainable production and consumption patterns”).

AGRICULTURAL
RESEARCH AND
INNOVATION ON
THE 2030 AGENDA



This book is intended for scientists, decision-makers, farmers, negotiators, international organizations, and anyone interested in understanding how agriculture can be part of the climate solution. It presents not only technologies, but also public policy strategies, territorial experiences, cooperation models, and ways forward.

In offering this book, we reaffirm Brazil’s commitment to regenerative agriculture, which is innovative and based on scientific evidence. We hope that this publication helps to strengthen alliances, share solutions, and accelerate the transformation needed for a fairer, safer, and more sustainable future in an increasingly challenging environment.

Carlos Henrique Baqueta Fávaro
Minister of Agriculture and Livestock

Silvia Maria Fonseca Silveira Massruhá
Embrapa President



Preface

This book reflects decades of dedication in Brazilian agricultural research, as part of an effort led by Embrapa to understand and address the impacts of climate change on agriculture. It is a record of the knowledge we have constructed and the solutions we have developed to sustain food production and environmental preservation.

In addition to expanding crop productivity, animal performance and the growth of planted forests, Brazil has overcome the immense challenges of the tropics and firmly established itself as a global benchmark in agriculture. Based on unprecedented contributions from agricultural research and the widespread incorporation of conservation practices, the country has reached the second phase of its agricultural profile.

Brazil has moved from food insecurity in the 1970s to producing 330 million tons of grain in 2025, guaranteeing food security for its more than 210 million inhabitants. It has also become the world's second largest exporter of food, making a decisive contribution to global food security.

The conservation-focused practice of no-till farming is used over 40 million hectares used to grow grain. In a similar area, biological nitrogen fixation is used with legumes by inoculating seeds with *Rhizobium* bacteria. For soybeans, the country's main grain crop, this technique ensures productivity with less dependence on chemical inputs.

In addition to boosting productivity and reducing production costs, both of these examples generate significant economic impacts. No-till farming helps expand stocks of organic carbon in the soil, while biological nitrogen fixation reduces nitrous oxide emissions by replacing synthetic fertilizers, removing carbon dioxide from the atmosphere. These emblematic practices reflect the strength of science in the development of sustainable agriculture (the main focus of this text) and are highly relevant in the context of the COP30, which will be held in Brazil.

Photo: Luiz Henrique Magnante (Embrapa)



The objective of this book is to use clear and objective language that is accessible to a broad domestic and international readership interested in the relationship between agriculture and climate change and scientifically-based innovation solutions, even if this audience is not made up of specialists in this subject or familiar with the Brazilian reality.

Along these lines, this book is structured in such a way as to offer in its first chapter an overview that spans the physical principles that explain global warming and its connection to agriculture, to the trajectory of international negotiations in search of solutions, to how Embrapa and its partners have organized to offer answers for the sector and face the main challenges. This first chapter sets the scene for the others, which delve into specific aspects within the context of climate science and solutions for Brazilian agriculture, addressing strategies, technologies and metrics for adapting to climate change and controlling emissions.

All the subsequent chapters utilize a standard four-part format: an introduction to the topic, current panorama, innovation solutions and future prospects. This organization establishes a timeline of past, present and future, highlighting how science has contributed to the evolution of each topic, as well as the opportunities and challenges that still lie ahead.

The chapters are ordered according to types of tools or approaches, in order to group the solutions together:

- Risk monitoring, adaptation and sustainability of national agriculture.
- Information management: databases, functionalities and metrics on the carbon balance in agricultural systems.
- Affordable and scalable techniques and tools for field monitoring of carbon and greenhouse gas data.



- The carbon balance for Brazil's main agricultural systems, protocols and representations.
- Carbon accounting and life cycle assessment for Brazilian agricultural products.
- Monitoring and inventories under the Paris Agreement, considering medium- and long-term challenges.

This initiative to present these solutions was the result of a coordinated effort by Embrapa through its Standing Committee on Carbon Dynamics, Greenhouse Gases and Adaptation in Agriculture, in conjunction with the Communications Office and with the support of the Managing Committee on the Climate, Natural Resources and Ecological Transformation Portfolio.

This project emerged out of a demand from the Research and Development Directorate, led by Director Clênio Nailto Pilon, with the commitment of the entire Embrapa board under the leadership of President Silvia Massruhá. The result is a collection of relevant contributions which can now be disseminated, adapted and incorporated in Brazil as well as abroad, according to different countries' circumstances and needs.

Our hope is that this book will contribute to an understanding of the relationship between Brazilian agriculture and climate change, as well as capacity building and technology transfer to Brazilian agricultural systems and to other countries that consider these resources feasible.

We hope you find it fruitful!

The Technical Editors





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CHAPTER 1

Climate change and agriculture

Natural resources, geopolitics and science

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Lívia Pereira Junqueira – Francislene Angelotti – Jorge Antonio Menna Duarte

Climate change and the development model

“It all started with a big ball of fire [...]”. This is how a now-retired researcher friend of mine used to jokingly refer to any lecturer or author who insisted on explaining their topic from the beginning of the universe or some very remote past, taking ages to get to their main point. I beg her pardon here (along with anyone else who is more familiar with this subject), because it is important to understand the origin of global warming and climate change. So we start here, with “a big ball of fire”: the Sun, the main source of energy for practically everything that happens on Earth (Figure 1.1).

Natural energy that keeps us warm

This energy from the Sun is transmitted in the form of short waves and reaches the top of the Earth’s atmosphere at an altitude of around one thousand kilometers. Much of this radiation is already reflected by the gases in the upper layers of the atmosphere, and continues to be reflected and absorbed by the various layers it crosses until it reaches the Earth’s surface. Along the way, the concentration of gases in the atmosphere increases until reaching the last layer, called the troposphere. The troposphere extends from the surface to roughly 12 km above sea level (Figure 1.2), and it is here that the highest concentration of gases is found, amounting to more than 80% of the gases in the entire atmosphere. This is also where practically all meteorological phenomena occur.

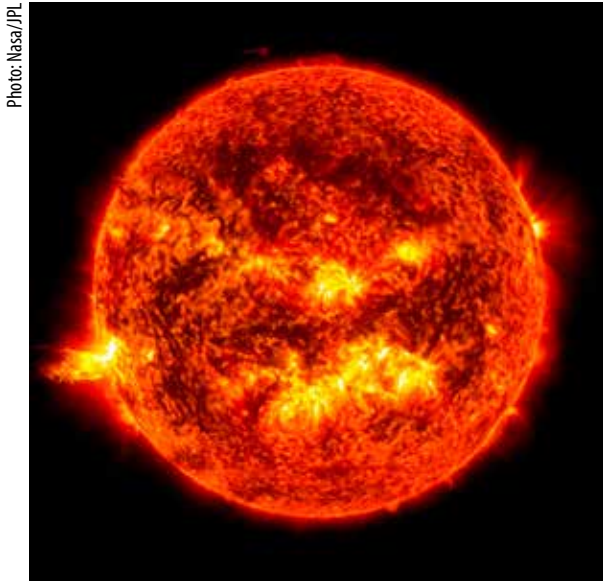


Figure 1.1. “A big ball of fire:” the Sun, the main source of energy for nearly everything that happens on Earth.

To understand global warming, it is important to emphasize that it is the energy absorbed by the gases in the atmosphere that causes its heating. Furthermore, the amount of this energy that is reflected, absorbed or transmitted as sunlight through the layers of the atmosphere depends on both the wavelength of the radiation and the size and structure of the molecules of the gases this radiation interacts with.

Let's return to sunlight, energy which reaches the Earth's surface in the form of a short wave. There this energy is absorbed by the Earth, heating it up, and it is relayed back out into the atmosphere in the form of a long wave. But on its way out in this new form, the energy interacts differently with the same gases in the troposphere that previously allowed it to pass through as a short wave. The energy radiated by the Earth is

partially absorbed by these gases, naturally warming the layer closest to the surface where we live. Without this warming, it is estimated that the average temperature of the Earth's surface would be around 15 °C lower.

Because this phenomenon resembles what happens in a greenhouse, where glass allows sunlight to enter but retains part of the heat that is radiated by the heated surface, creating conditions that foster plant growth, this natural phenomenon is known as the greenhouse effect. Figures 1.3 and 1.4 show the interaction between solar radiation and the atmosphere and how this radiation behaves inside a glass greenhouse, respectively.

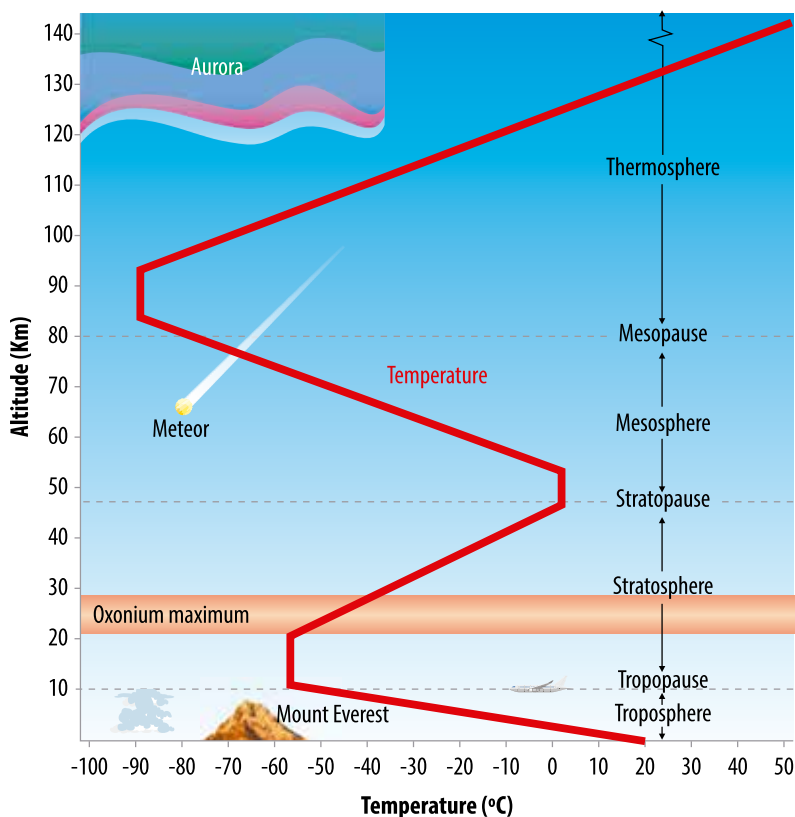


Figure 1.2. Atmospheric layers and temperature behavior as a function of interactions between solar radiation and the gases that make up the atmosphere.

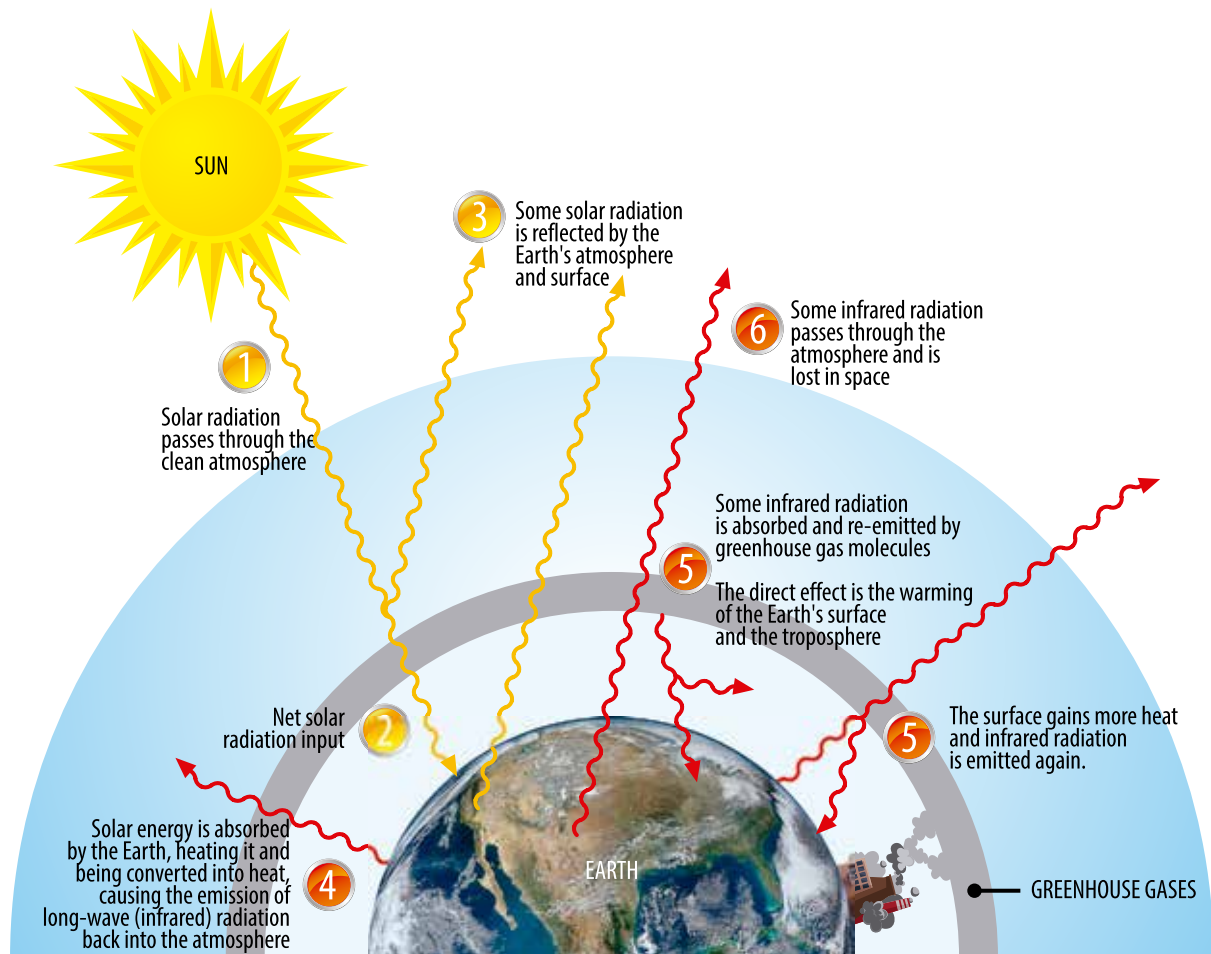


Figure 1.3. Interaction between solar radiation and the atmosphere and the natural greenhouse effect.

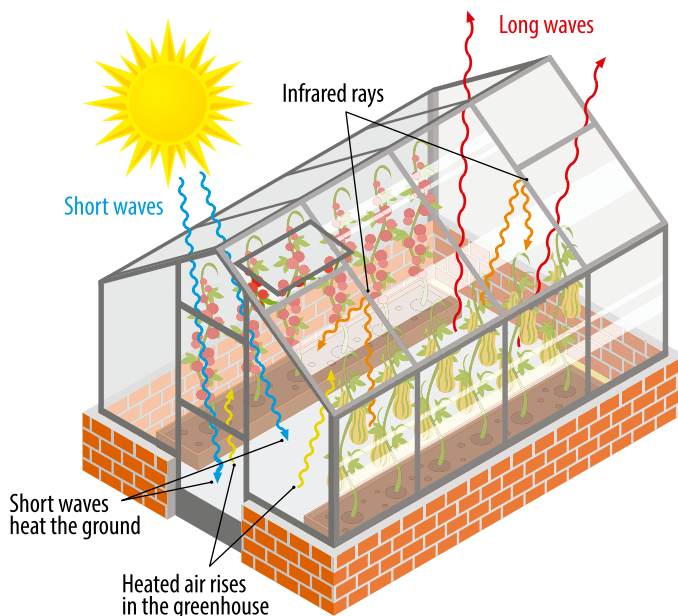


Figure 1.4. Interaction between radiation and internal heating in a glass greenhouse.

Can humanity change a natural planetary process?

Until very recently, few people thought that human actions could affect major natural phenomena. The current model of economic and social development considered natural resources to be infinite and believed that they could be used almost indiscriminately, without any major impacts, let alone global consequences. However, since the Industrial Revolution and the discovery of fossil sources of energy like coal, natural gas and oil, this panorama has begun to change profoundly.

These combustible hydrocarbons were generated when geologically stored organic matter was buried at high pressures and temperatures during past eras, until the tectonic plates settled and established the continents and oceans with their current terrain. They no longer participated in or influenced the energy cycle on the Earth's surface. But while their discovery and use permitted the Industrial Revolution and the rapid technological development that has been achieved to this day, this activity also began to release gases derived from these hydrocarbons into the atmosphere, raising their concentrations. And the interaction between the long waves we described earlier and greater concentrations of these gases significantly increases absorption of the radiated energy, causing an increase in the average temperature of the Earth's surface, the global warming. This is why these gases are known as greenhouse gases (GHG), and the warming they cause is a direct result of human activities and the development model founded on intensive use of energy from fossil sources. For this reason, as the reports by the Intergovernmental Panel on Climate Change (IPCC, 2014, 2023) conclude, this global warming is anthropogenic, since it is mostly caused by gases resulting from human activities, and is altering the normal climate pattern, known as climate change.

The climate has changed! Now what?

It is consequently clear that there is a nexus, or connection, between climate change and development models and how we live in society, and how products and services are made in the various sectors of the global economy. And it is vitally important to understand what effects these models have on the climate, how they contribute to global warming, what gases they emit and how much, and what viable ways can be used to remove these gases from the atmosphere, using natural or artificial processes. In turn, it is also essential to identify or develop ways of understanding the impact of climate change for natural environments and life on the planet (including human life), and to adapt to whatever consequences of global warming that cannot be mitigated.

Although climate change is a large-scale spatial and temporal phenomenon that can only be perceived over decades or even a century, its impacts are increasingly present, growing and intensifying, and increasing in frequency (IPCC, 2023) to the point where we are no longer talking about climate change but rather climate crisis or climate urgency. We use the term "climate" to refer to the normal phenomena that occur in the troposphere, namely meteorological events, behavior that is observed and defined over decades around an average cycle of monthly and annual temperatures that repeat in a normal variability range. When this average long-term cycle changes it is called climate change, the term we prefer to use throughout this book.

The terms "crisis" and "urgency" are antagonistic in origin (in terms of etymology) when used with regard to the climate. Despite this etymological antagonism, the meaning used today implies a need for rapid action. Given the difficulty of changing our development models, namely the inertia related to social and economic behavior,

this problem has worsened to the point of urgency. This means not much time is left for us to make decisions and take action to stop global warming from intensifying even more, and to minimize its impacts on various sectors, known as mitigation, while also decreasing the vulnerability and exposure of production systems to what cannot be avoided, known as adaptation. Figure 1.5 shows vulnerability, exposure and danger as factors that determine the risks and impacts associated with climate change. It also depicts the relationship between these factors and the socio-economic model and processes, GHG emissions, governance of these dynamics, and adaptation and mitigation activities that may be able to reduce risks and impacts.

How does agriculture relate to all this?

In addition to sectors like industry and transportation, which clearly is the primary

and essential user of coal, natural gas and oil, agriculture¹ also contributes to global warming and climate change, to a greater or lesser extent: through inputs from fossil sources, conversion of natural areas into arable land and the consequent loss of biodiversity, soil and livestock management and other activities intrinsic to production models. At the same time, because this sector is closely linked to and dependent on the natural environment, it is directly affected and impacted by climate change. And furthermore, because of the nexus with other sectors of the economy, this impact is reflected both in food production (which itself is linked to people's well-being, quality of life and health) as well as in the production of fiber and energy (which are used directly or as an input for industrial processes).

Obviously, in addition to the nexus between agriculture and food production and these and other sectors there is also the relationship with other countries, demand for food and

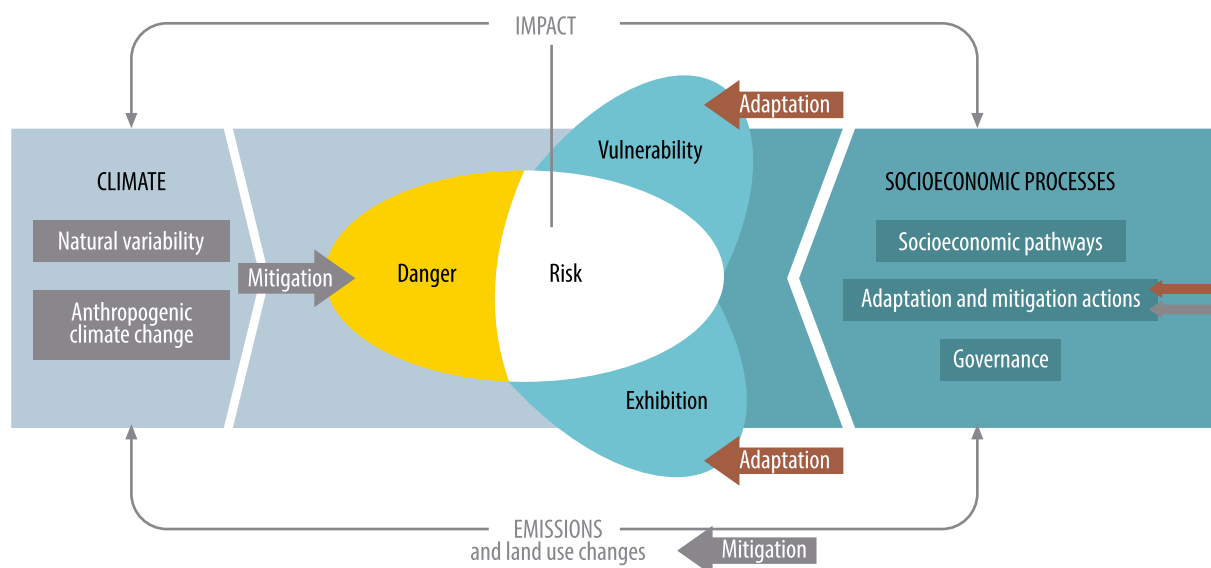


Figure 1.5. Climate change mitigation and adaptation efforts: risk components and the need for adaptation and mitigation activities according to the socio-economic pathways or development models adopted.

¹ Agriculture is considered here to encompass all productive activities in the rural ecosystem, including cultivation of vegetable/agricultural crops, livestock or animals, forestry or timber production, and integration of these products into more complex systems.

other products, competition from commercial products, and negotiation of multiple and often conflicting interests at the global level, which can hinder progress toward solving this problem.

But before we analyze the geopolitical context, it is important to turn our attention to the process that takes place for agricultural crops, forests, and animal agriculture, or even within the production environment as well as in nature. This approach is fundamental for us to understand what will be discussed later in this chapter and beyond with regard to adaptation and mitigation actions and negotiations around international regulation.

We also need to assess the impact of climate change, which agriculture must adapt to. Higher temperatures can cause physiological changes in plants and animals, directly affecting the processes through which they absorb nutrients, grow, reproduce and generate fruit and seeds, and ultimately complete their life cycle. In plants, for example, warming can cause them to grow less or stop producing, or abort flowers and fruit because the range between the minimum and maximum daytime temperatures falls outside the optimum limits for their development. Animals can have problems with overheating and may start to eat poorly, lose weight or miscarry their offspring, for example.

Rising temperatures also increase demand for water by plants and animals, as well as increase evaporation of water from plant and soil surfaces, a phenomenon which occurs together with transpiration in the process known as evapotranspiration. And while the warming of the atmosphere boosts demand for water from the soil for evapotranspiration, various regions around the world and most of Brazil face projections of less precipitation or precipitation concentrated into shorter periods of time, reducing water availability. Like a bank account where you spend more than you put in, the water balance becomes negative, leading to water deficit. This means there is not enough

water for plants to meet their needs in order to grow and produce properly.

The risk involved in water shortages is clear, with serious repercussions such as reduction or even collapse of entire harvests at the farm or even regional level, not to mention increased frequency of extreme events such as storms, hailstorms, heat waves and prolonged droughts (like the flooding that affected most of the Brazilian state of Rio Grande do Sul in 2024, or extensive drought in the Midwestern region of the country that delayed planting and reduced harvests).

Adaptation and mitigation in agriculture

In agriculture, the solution to these problems related to stress caused by rising temperatures and reduced availability of water for plants and animals may lie in genetic improvement and the development of resistant and/or tolerant cultivars. Technological advances in agriculture have also made it possible to adopt more efficient management practices, combined with the use of inputs adapted to adverse conditions, which helps mitigate the impacts of climate change to some extent.

Mulching with straw, agricultural by-products or even live plants can be used to cover the soil, reducing temperatures at the soil surface and in the planting area. Practices that boost the amount of organic matter in the topsoil permit greater water infiltration and storage, while precision irrigation techniques optimize water use. No-till planting practices that involve crop rotation and mulching or soil cover throughout the cycle, diversification and integration of systems, regenerative agriculture for soil health and biodiversity (including remediation of degraded areas), and techniques to sustainably intensify production all make it possible to produce more each year in the same area.

Within the context of sustainable intensification, this means not only increasing the productivity of one crop, but especially diversifying production in the same area through intercropping or integrated crops; this may involve integrated crop-livestock, agroforestry or agropastoral systems, as well as producing two or even three crops a year. These methods offer ways to promote sustainability, provided that the inputs and management practices adopted do not increase the carbon footprint of the resulting products. Sustainable intensification is also a way of reducing pressure on biomes and their natural ecosystems, and reduce biodiversity loss.

The biodiversity of ecosystems, from microscopic organisms to plants and animals we can see, is a source of biological resources that maintain the soil microbiology, boost availability of nutrients, and are also responsible for biological nitrogen fixation (BNF). Use of these biological inputs in a production model that promotes soil health is essential for mitigation and for adapting agriculture. It is important to develop ways to sustainably manage and restore forests and produce non-timber resources that generate value for the standing forest in order to reduce society's pressure on natural biomes, which also need to adapt to climate change.

Extending beyond bioinputs for sustainable production, we also need technologies and infrastructure for reservoirs and for efficient storage and use of water, along with irrigation techniques that avoid losses and waste. The development of machinery and new mechanization techniques that can prevent soil compaction or make it possible to carry out water and soil conservation projects also contributes to these efforts. Planting in the shade or even under protective structures (including industrialized structures outside the rural environment) may also be used as alternatives, as long as their environmental impacts and effects on food and nutritional

security are studied. In short, a wide range of equipment, techniques and best practices have already been developed and can be used. New techniques and methods may also emerge to reduce this impact and expand the adaptive capacity of agricultural systems.

From the viewpoint of mitigation, many of these same technologies can be used because they tend to be both adaptive and mitigating. These include incorporating vegetation cover, organic matter, bio-inputs or BNF, as well as other specific techniques for reducing emissions from agriculture. The focus, in this case, is on avoiding GHG emissions by reducing direct use of fossil fuels and inputs derived from these sources, minimizing deforestation and conversion of natural areas, and avoiding tilling the soil, which releases much of the carbon stored within. Meanwhile, it is possible to expand the use of techniques that remove GHG from the atmosphere and store carbon in the elements of the agricultural ecosystem, especially in soil or trees.

Many of these innovative techniques or solutions (whether they focus more on adaptation or on mitigation), as well as metrics and indicators to monitor or inventory progress, will be detailed in the chapters ahead.

Connecting the dots

Clearly, the greenhouse effect, the same natural process that maintains the Earth's average surface temperature at levels suitable for plant and animal species (including humans) to survive, can be altered by the development model which is founded on fossil fuels.

According to the latest IPCC report (2023), this is the main cause of global warming, and impacts various sectors of the economy. This report also points out that the average global temperature has already reached 1.1 °C above the mean value for the pre-industrial period, and that if we

consider only continental regions this figure rises to 1.6 °C. The 2024 *Global Climate Highlights* brief by the European Union's Copernicus Institute of Sustainable Development (Global Climate Highlights, 2025) notes that 2024 was the first year when the average global temperature clearly exceeded the 1.5 °C limit and reached between 1.57 and 1.60 °C above pre-industrial levels.

Practically all sectors of the economy contributed to this temperature increase, which at the same time has a direct impact on all of them. Globally, agriculture is responsible for 11.7% of emissions.² Within this context, Brazil accounts for 2.1% of global emissions, and Brazilian agriculture around 1% (Ge et al., 2024). But in the national context, agriculture contributes 30.5% of emissions³ and changes in land use account for 39.5% (Brazil, 2024). In order to reduce the impact of these emissions at a global or national level a new development model is required, bearing in mind that this is a global phenomenon with multiple dimensions (environmental, economic, social and political) and that a transition to more sustainable, resilient and technologically adapted production systems in all sectors is urgently needed.

This phenomenon also significantly affects agriculture and, in turn, food security. A 2008 study in partnership between the Brazilian Agricultural Research Corporation (Embrapa) and the State University of Campinas (UNICAMP) (Deconto, 2008) indicated a reduction of roughly 35 to 40% in areas with low risk potential for soybean production in 2070, depending on the IPCC scenario adopted in the projection ("optimistic" or "pessimistic," respectively). With the exception of sugar cane and cassava, slightly smaller reductions have been projected for Brazil's main food crops. Although nationwide the

area with low risk potential for cassava increased, in the Northeast low-risk area decreased.

The *Brasil 2040* study coordinated by the President's Special Secretary for Strategic Affairs (Brazil, 2015) pointed out trends in agricultural crops for 2040, which were coupled with an economic model to estimate changes in land use for agricultural production as a function of projected climate scenarios. These estimate indicated reduced productive potential for low agro-climatic risk during the projected period up to 2040, and more significant impacts on soybean cultivation in all the scenarios presented up to 2040; some municipalities are even expected to stop producing soybeans because they are classified as facing high levels of climate risk.

It is clear from these studies that both the average upward trend in temperature and the extreme events projected by the IPCC (2023), combined with inadequate management of the agro-ecosystem and natural ecosystems and not adapting production techniques to the new climate reality, could lead to serious consequences such as water scarcity, flooding, soil degradation, fires, loss of biodiversity, and food insecurity.

Agriculture plays two roles in relationship with this new reality: it is both a victim and an important vector for intensifying global warming and resulting climate change. Implementing agriculture that is entirely low-carbon, with little or no dependence on fossil-based inputs and completely detached from deforestation, which develops and adopts forms of sustainable management and forest restoration as well as production of non-timber forest resources that generate value for standing forests and reduce pressure on biodiversity, is probably the most effective way to reduce contributions to the intensification of this phenomenon by the sector.

² Total overall emissions, excluding emissions from changes in land use.

³ Total overall emissions, including emissions from land use change.

The nexus between health, climate and food production

On the other hand, the impact on agriculture (since this is the sector most closely tied to and dependent on the natural environment) highlights the nexus, or connection, between climate change, food and nutritional security and food sovereignty. This connection is reflected in food production capacity, especially in countries like Brazil where agriculture is one of the largest productive sectors and a pillar of its economy, with agribusiness accounting for 23.5% of national gross domestic product (GDP) in 2024 (CEPEA, 2025). Planning investments in adaptation, mitigation and prevention as we face an undesirable future are required to ensure food and nutritional security, as exemplified here and in the other chapters of this book.

When it comes to food and nutritional security and food sovereignty (in other words, the country's ability to decide how to guarantee its population the independence to grow, distribute and ensure access to high-quality food in quantities required for adequate nutrition), this investment benefits other sectors, since it is clearly linked to health, well-being and quality of life of the population. This is related to the concept of One Health. The nexus with the One Health framework ranges from plant and animal species (including humans) to ecosystems and the planet itself, promoting quality of life, the use of nutritious and functional foods and healthy interaction between these species and the environment, involving the broad concept of ecophysiology, or ecosystem function, in the various aspects and factors that affect the health of the Earth.

And obviously, given the complexity of development models in various regions of the world and their commercial, political and social relationships, there is a strong nexus between food security, biodiversity and the

environmentally efficient and sustainable use of natural resources, especially soil and water. Competition between the urban, industrial and rural sectors for water use demands alternatives for water storage and efficient use at the various scales of agricultural production.

In the energy sector, agriculture plays an essential role in the search for renewable alternatives as part of the transition to an economy with little or no dependence on fossil fuels. Particularly important in this context is the production of bioenergy from biomass and biofuels, and use of rural areas to generate wind, solar and hydroelectric power. There are also connections with storage and distribution logistics, transport modes and industrial processes that use fibers and other biological inputs.

Cultural aspects and socio-productive and digital inclusion must permeate and be present in all these nexuses, seeking alternatives to define new models of sustainable development in the broadest sense of the term (in other words, development that involves economic, social, environmental, institutional and geopolitical aspects).

Finally, integration of scientific support into the formulation of public policy, as a way of exercising science diplomacy⁴ and to monitor effectiveness, is essential if we are to make a viable and efficient transition to an ecological development model that emits less GHG and is based on renewable resources, bioeconomy and the circular economy.

We need to talk

The scientific evidence obtained through studies on advances in international knowledge on this subject, coordinated by the IPCC over cycles of roughly seven years, highlights the urgent

⁴ The concept of science diplomacy will be addressed in more detail in the subsection below.

need for a global effort to transition to more sustainable, resilient production systems that are technologically adapted to the new climate reality and future projections.

Historically, when faced with this complex international context marked by global warming and the need for global efforts to mitigate the effects of climate change, the United Nations Conference on Environment and Development (Rio 92, also known as the Earth Summit) held in Rio de Janeiro in 1992 established three Framework Conventions on issues that demanded — and still require — global attention and effort: the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (UNCBD), and the Convention on Climate Change (UNFCCC). The history and details of the UNFCCC are described below, particularly with regard to the agricultural sector and contributions by Embrapa and its partners, the focus of this book.

Climate geopolitics within the scope of the Convention

The beginnings of the Convention

The heart of the UNFCCC consists of a goal that is relatively simple to put into words but represents an extremely complicated challenge to put into practice: to understand how individual countries contribute to GHG emissions, and identify the sources of these emissions within the economic process and unique activities of each country.

To achieve this goal, in the early stages of the international negotiation process the UNFCCC gave the IPCC a mandate to carry out a study exploring how to make this goal a reality. The IPCC then set out to create a comprehensive scheme that would account GHG emissions

in each country in a transparent, accurate, complete, consistent and comparable manner.

The resulting set of methodologies was adapted so all nations could report their emissions, based on data for the specific activities of their economic sectors and emission factors designed according to their geographical and economic circumstances. This primary set of methods adopted by the UNFCCC serve as the foundation for drafting the National GHG Inventory and the National Communication, using the most basic methodology proposed by the IPCC.

However, merely identifying the origin of emissions was in no way sufficient to meet the ambitions defined by the UNFCCC, as presented in Article 2 (Convention on Climate Change, 1992), transcribed below:

ARTICLE 2

OBJECTIVE:

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

As early as the first Conference of the Parties (COP1), held in Berlin from March 28 to April 7, 1995, it became clear that the language of the newly adopted Convention was far from sufficient to meet the challenge of stabilizing GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system. In fact, many variables were still unknown at the time, but there was one certainty, which led all those

countries to universally adopt the Convention: much work would be required to make the transition from a fossil fuel-intensive economy to a greener, more sustainable future.

Although the Convention laid the foundations so that a change in the global economic model could thrive (involving energy that was not derived from fossil fuels, more environmentally sustainable, socially relevant and economically efficient), it was up to each country to develop its own national strategies and design its own scientific and technological processes. What in 1995 was just planning for the future would have to be implemented by each country, in the form of domestic public policies.

At the time it was still unclear what the specific “level that would prevent dangerous anthropogenic interference in the climate system” would be. The primary decision of COP 1, consequently, was to establish a two-year discussion process that would result in the drafting of a protocol within the framework of the Convention, designed to help countries understand and develop strategies to shift their economies towards the greener future envisioned by society.

After a few years of global discussions on the issue of climate change, this process resulted in the Kyoto Protocol, the first international agreement signed within the UNFCCC framework. Annex I of this agreement contains a list of “parties,” in other words developed countries or blocs of countries (such as the European Union) committed to emission reduction targets, the so-called Annex I countries.

Inducing a new perception and new parameters for the global economy

Discussions and agreements of this nature led to the realization, at least among the more attentive countries, that the ability to report data

in line with the national reality could constitute a competitive advantage. However, this would require investment in new technologies, research and infrastructure, all of which depend in turn on essential and urgent planning.

In this way, through this structuring the UNFCCC intrinsically also began to foster the development of new sustainability and competitiveness indicators for domestic policies and raising of public awareness about the issue of climate change, through structured records in a global GHG emissions inventory process. With this framework, risk assessment associated with planning, adapting installed infrastructure, and strategic information management become fundamental elements and also involve new challenges, while cooperation between countries or regions in increasingly interconnected networks and markets faces pressure to align with environmental and social sustainability indicators. This is an irreversible process that is inherent to social and economic transformation towards the post-petroleum era, which will favor countries that are better equipped, both technologically and in terms of their ability to organize to define and implement sustainability indicators that reveal the convergence of international, national, and sub-national standards.

Certainly, investments in their own strategies to characterize national emissions and removals in sensitive and strategic sectors of the economy have always been a priority for countries that already have emissions reduction targets in place. For example, the European Union: this bloc has signaled its concern with “carbon leakage” caused by imports of items that involve carbon-intensive production, through measures that include negotiation of trade instruments.

Countries that export to the European Union must be aware of the new guidelines and be prepared to maintain investments in monitoring and quantifying the carbon footprint of their

products, and also ensure that other aspects and indicators capable of conferring quality and added value to products are visible to the consumer. All these measures and attention to international perceptions of the parameters of “fair, healthy and ecologically correct” are important to maintain competitiveness on the international market, not only in relation to exports to Europe but also the regions it influences.

This European vision will try to reinforce the bloc’s relative difference in emissions compared to its international competitors, minimizing the importance of its share of global GHG emissions (less than 10%) and emphasizing its achievements over the last few decades toward reducing absolute emissions, positioning itself as a leader in the global transition to a net-zero emissions economy. However, the European bloc is the fourth largest GHG emitter in the world, behind China, the United States, and India (Friedrich et al., 2023), with the energy sector accounting for 75.7% of its emissions.

Contributing to Brazil’s position

Brazil ranks seventh among the largest GHG emitters, according to an assessment by the World Resources Institute (Friedrich et al., 2023) based on data from 2019. Since at least 2009, Embrapa has participated in this discussion process and has taken a leading role in generating data and strategic intelligence with regard to monitoring processes that involve agriculture and climate ambition at the international level, particularly with a focus on competing markets. Brazil is not an “Annex I country,” but the discussions and negotiations that took place after the Kyoto Protocol to construct a more transparent and effective model culminated in the Paris Agreement and its new regulations. Within this context, the parties that signed the Convention committed themselves to global efforts to reduce emissions,

by voluntarily establishing their Nationally Determined Contributions (NDCs). European regulations present 10 criteria for guiding policies and actions towards climate neutrality. The first four are economic/competitive in nature, which demonstrates the relevance of economic issues in dealing with environmental issues:

- Cost/benefit ratio and economic efficiency.
- Competitiveness of the EU economy.
- Best technology available.
- Energy efficiency, energy accessibility and security of supply.
- Justice and solidarity between and within member states.
- The need to ensure environmental effectiveness and progress over time.
- Investment needs and opportunities.
- The need to guarantee a just and socially acceptable transition.
- Developments and international efforts undertaken to achieve the long-term objectives of the Paris Agreement and the ultimate goal of the UNFCCC.
- The best available and most recent scientific evidence, including the latest IPCC reports.

Competitiveness of each of the blocs and countries over the coming decades will consequently be the result of effective investments in research, development and innovation, linked to the ability to identify vulnerabilities and effectively implement a systematic adaptation plan capable of reducing the impacts of climate change on the economy, while planning and strategic investments simultaneously take place to reposition the respective economies in new development models independent of fossil fuels, in a “post-petroleum” era based on renewable energy sources. In this sense, the European Union is

undeniably at an advanced stage of planning, since it has a strategy and defined, structured priorities in the form of the European Green Deal.

It is up to the relevant sectors of the Brazilian economy to understand the vulnerability inherent in lack of planning and long-term goals that could leverage competitiveness, based on robust and internationally recognized scientific data that can catalyze competitive differentials in tune with the emerging environmental issues of sustainability.

The role of the Intergovernmental Panel on Climate Change in estimating emissions

As we have seen so far, GHG emissions are a consequence of every economic activity that takes place within a country. Based on the discussions on this relationship between economic activities and GHG emissions which took place at the COPs that signed and adhered to the UNFCCC, the first commitment agreed by the countries in the Convention was established, a crucial milestone that is presented in Article 4 (Convention on Climate Change, 1992):

ARTICLE 4

COMMITMENTS

1. All Parties, taking into account their common but differentiated responsibilities and their specific national and regional development priorities, objectives and circumstances, shall:
 - a) Develop, periodically update, publish and make available to the Conference of the Parties, in accordance with Article 12, national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies to be agreed upon by the Conference of the Parties;

Based on this decision, the Intergovernmental Panel on Climate Change (IPCC) was given the

power to develop the set of methodologies that were subsequently agreed upon at the COP and today guide the process of drafting national inventories, also forming the basis of the Biennial Transparency Reports (BTRs) under the Paris Agreement.

It is important to note that the IPCC's contributions to developing the inventory methodology for the UNFCCC date back to 1994, when the original guidelines for national greenhouse gas inventories were made available. These guidelines were revised in 1996, comprising a common and widely adopted set of methodological guidelines that until very recently formed the basis for national inventories for all countries (developed as well as developing). Throughout this initial period of development for international processes, Embrapa supported the Ministry of Science and Technology in drafting Brazil's National Inventory, originally using the 1996 IPCC methodologies (IPCC, 1996).

This methodology has been made available in both digital and printed format, divided into three volumes. Some relevant updates were made after the 1996 guidelines, but a major methodological revision was not published until ten years later, in the form of the 2006 methodological guide (IPCC, 2006), this time in five digital volumes. A new update was subsequently released in 2019 (IPCC, 2019), which can be adopted in new BTR submissions.

Brazil was the first country to sign the UNFCCC after the United Nations Conference on Environment and Development held in Rio de Janeiro in June 1992, a measure which was ratified by the national congress in 1994. It was also the first country to establish a National Designated Authority for the Convention: what at that time was the Ministry of Science, Technology, Innovation and Communications (MCTIC). The MCTI is currently responsible for structuring the data sources for activities and

emission factors used to develop and compile the inventory for the current update cycle of the National Communication (NC) and the BTRs, in line with the applicable rules of the UNFCCC and the Paris Agreement.

Brazil has always given strategic importance to the commitment to present its NCs, and has already submitted four (2004, 2010, 2016 and 2020) with the National Inventory attached, and four Biennial Update Reports (BURs) in 2014, 2017, 2019 and 2020, while the Kyoto Protocol rules were still in force. In 2024, the country submitted its first BTR, under the rules of the Paris Agreement. These documents, while taking into account current methodological limitations, compile official sources of information and structure the data available for estimates of GHG emissions and removals that characterize national production systems.

Estimates of GHG emissions and removals from the agricultural sector are based on methods that can use: a) standard IPCC factors (Tier 1); b) data on GHG-emitting activities in the country (commonly referred to as “activity data”), combined with emission factors estimated from official national sources (Tier 2); or nationally developed emission estimate models that incorporate activity data and emission factors more suited to the realities of national production systems (Tier 3). This latter approach is not yet used to estimate official emissions from the agricultural sector in Brazil, but efforts are underway to develop models that can more adequately represent the reality of national production systems in tropical and subtropical environments.

Currently, the 2006 IPCC Guidelines are the most recent and set of rules agreed upon for estimating GHG emissions and drawing up national inventories. They have been adopted as the standard for the Enhanced Transparency Framework (ETF) of the Paris Agreement. The 2019 update is probably the most relevant and

sensitive revision, since it complements gaps in the 2006 guidelines, especially with regard to methane emissions from fugitive gases in the energy and industrial sector, as well as emissions from liquid effluents in the industrial sector.

In addition to the methodological guidelines, the IPCC is also responsible for developing the Inventory Software, a tool to support countries as they draft their national inventories and implement the Common Report Format (CRF). Within the UNFCCC, there is a secretariat responsible for maintaining and making GHG data available on a comprehensive and dynamic web platform that combines databases and different functionalities for consultation. This structure comprises the Convention’s framework of tools for understanding and assessing GHG emissions from both Annex I and non-Annex I countries.

It is important to clarify that Annex I is essentially made up of developed countries, while the group of non-Annex I countries is more diverse and consists of the other signatories.

Science and innovation for agriculture adapted to climate change

It is already clear from the previous subsections that agricultural science (predominantly public institutions) has played and will continue to play a central role in moving towards a development model that will allow us to overcome the challenge of mitigating global warming and adapting to the effects of climate change that cannot be avoided.

Science diplomacy

As a national agricultural research institution, Embrapa has focused strongly on sustainability, addressing the effects of climate change and

reducing GHG emissions from agriculture in management documents such as *Visão 2030* (Vision 2030) and *Planos Diretores da Embrapa* (Embrapa's Master Plans, PDE) VI and VII containing the Strategic Objectives (Embrapa, 2015, 2020). The most recent 2024-2030 Embrapa Master Plan (Embrapa, 2024) presents one of nine strategic objective endpoints that specifically focuses on natural resources and climate change.

The introduction to *Visão 2030 – O Futuro da Agricultura Brasileira* (Vision 2030 – The Future of Brazilian Agriculture) (Embrapa, 2018) states that

The analyses carried out in this document contribute to strategic decision-making by Embrapa and the various agents and actors at all stages of the agricultural production chains, with a view to Brazil's continued sustainable development. [translation ours]

This document also contains a chapter entirely dedicated to climate change, with subsections entitled Vulnerability, Adaptation and Mitigation; International Commitments; Fostering Science and Technology; and Challenges.

Within this context, Embrapa is contributing to the transition towards a more sustainable development model, which considers social and economic transformation, an improved environmental balance, and advances in quality of life and One Health. This process is intended to reduce dependence on or even completely restrict the use of fossil fuels in favor of renewable forms of energy, in order to decrease or even neutralize the balance between GHG emissions and removals.

Scientific contribution is a basic element for national and international negotiation of collaboration agreements, and for defining public policies and decision-making for the national agricultural sector. Embrapa has also been a very active contributor in this context of global geopolitics, offering support for international negotiations since the topic of agriculture

was discussed by the UNFCCC in 2009 in Copenhagen; at that time, it was part of sectoral approaches within an item of the Convention where some sectors were grouped together and later discussed separately. This activity fits in well with what has been called “science diplomacy.”

Science diplomacy is an approach that uses science to solve global problems, promote collaboration and support public policy decisions. According to The Royal Society (2010), it combines science, technology and foreign policy to address challenges such as climate change, using science to strengthen cooperation between institutions, countries and sectors in order to assist in creating public policies and solutions for global issues.

In the case of Brazilian agriculture, Embrapa uses scientific diplomacy to support the definition of public policies and participation in international agreements that promote sustainable agricultural practices, reduce climate impacts and support decisions that balance economic growth, environmental protection and quality of life. In practice, this means using data and research to support initiatives that connect scientists, governments and communities to make decisions that enable the development and wider adoption of innovative solutions, such as agricultural technologies that emit less GHG or systems that help governments and farmers plan their crops amid unstable weather conditions. In this way, Embrapa's scientific diplomacy has a direct impact on Brazilian agriculture and on the international stage.

Two cases of these efforts, among the many examples of support for defining public policies we will present in this chapter and throughout this book, are the Agritempo system⁵ and the Zoneamento Agrícola de Risco Climático (Agricultural Climate Risk Zoning, ZARC)⁶

⁵ Available at: <https://www.agritempo.gov.br/br>.

⁶ Available at: <https://www.embrapa.br/rede-zarc-embrapa>.

(Monteiro et al., 2024). Both help Brazil adapt to the climate and plan a more resilient agriculture. By developing tools like Agritempo and ZARC, Embrapa is helping Brazil to meet global commitments such as the Paris Agreement, which is intended to reduce GHG emissions and promote adaptation to climate change. These initiatives also strengthen collaboration between scientists, governments and farmers, creating a more sustainable agricultural model.

Embrapa's scientific work is also used to negotiate international partnerships, share technologies and promote agricultural practices that respect the environment. For example, Brazil can share its experiences with ZARC with other countries that face similar climate challenges, strengthening global cooperation.

Despite the progress, obstacles still remain. Climate change is making the weather more challenging, and requires production and monitoring systems to be constantly updated with new technologies and data. We also need to invest in training farmers and in communication so that these tools can reach everyone, especially small producers.

Considering the projections for our future, it is essential for Embrapa to continue using scientific diplomacy to develop and ensure adoption of innovative solutions, like technologies that further reduce GHG emissions and promote the use of renewable energy in agriculture. These efforts will help Brazil achieve a more balanced development model, with benefits for the economy, the environment and society.

Structuring research into climate change and agriculture

This work, with an emphasis on sustainability, tackling the effects of climate change and reducing GHG emissions in agriculture, has been supported by the networks of researchers and the physical and organizational infrastructure

that Embrapa has constructed over the past few decades.

After hiring over 30 researchers specifically for the area of climate change and agriculture in 2006, Embrapa implemented its Plataforma de Pesquisa em Mudança Climática e Agricultura (Climate Change and Agriculture Research Platform) in 2007 (Figure 1.6). This corporate effort has permitted research, development and innovation solutions to adapt agriculture to the effects of climate change and reduce GHG emissions from agricultural activities. Four pillars or structuring lines of work were defined: simulating future scenarios for agricultural crops; simulating future scenarios for pests, diseases and weeds; carbon balance and controlling GHG emissions in production systems; and adapting production systems to the impacts of climate change.

Six national projects were carried out between 2009 and 2013 with networks over to 100 researchers each, in all of Brazil's biomes (Figure 1.7). Three of these projects focused on vulnerability analysis and adaptation alternatives: two addressed scenario simulation and vulnerability analysis for crops (Simulação de Cenários Agrícolas Futuros [Simulation of Future Agricultural Scenarios], SCAF) and the occurrence of plant health issues (ClimaPest), while the third focused on the three interconnected issues of agriculture, water resources and climate change (AgroHidro). Three additional projects focused on the third pillar, carbon balance and mitigation: for forest species (Saltus), livestock (Pecus) and agricultural crops (Fluxus).

The fourth pillar defined by the platform was addressed differently; instead of one large project integrating the country's various biomes, several specific projects were developed for each crop, with a focus on genetic improvement. Within this context, still in the last century soybeans and wheat have been adapted to tropical climates, and more recently cultivars of irrigated rice,

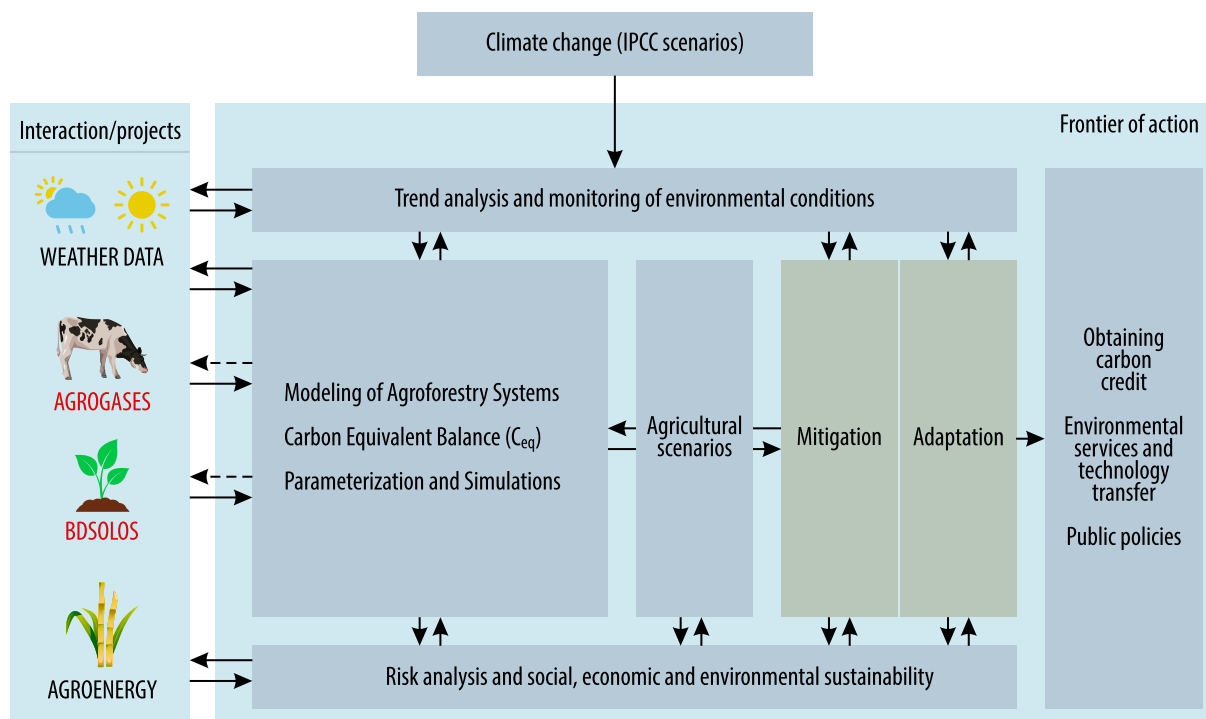


Figure 1.6. Embrapa's Climate Change Platform: structure, main elements and connections between elements.

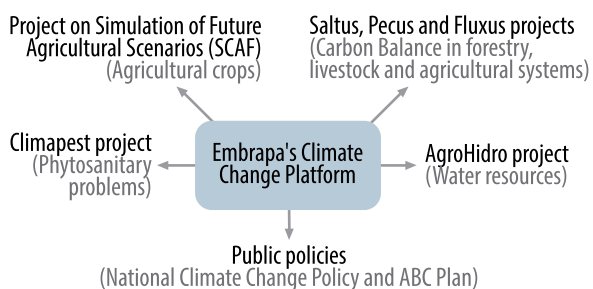


Figure 1.7. National-level projects linked to Embrapa's Climate Change Platform.

coffee, grapes and lettuce have emerged that are adapted to the tropical conditions in northern Brazil, resist the diseases that are common in these regions, or are more tolerant of high temperatures and drought. These are just a few examples of commercial products adapted to harsher climatic conditions which have been developed through traditional plant breeding as well as advanced genomic techniques. Several of the adaptive techniques mentioned at the beginning of this chapter have also been

employed as alternatives for adapting to the impacts of climate change, in both projects with a more specific focus and large national research networks.

The studies and results from these national research networks, as well as collaborations with researchers from Embrapa's international relations and parliamentary advisory areas, have supported the platform's strong efforts in defining public policies and Brazil's participation in international negotiations on agriculture and climate change within the UNFCCC, all based on science, as advocated by scientific diplomacy.

In addition to ZARC, other examples of public policies on climate change and agriculture that have received such support include the Política Nacional sobre Mudança Climática (National Policy on Climate Change, PNMC), the Plano Setorial para a Agricultura de Baixa Emissão de Carbono (Sectoral Plan for Low-Carbon Agriculture, also known as the ABC Plan),

and the Plano Nacional de Adaptação (National Adaptation Plan, PNA), in its chapter on agriculture and its respective goals, as well as the drafting of various technical notes on legal proposals related to this issue. More recently, Embrapa has supported the analysis and definition of issues and legislation linked to other sectors like the carbon market, environmental services, forests and biodiversity, One Health and the Programa Nacional de Conversão de Pastagens Degradadas (National Program for the Conversion of Degraded Pastures, PNCPD).

A new institutional instrument focused on the country's main challenges

Since 2012, Research Portfolios have been established as an institutional instrument for strategic and tactical support to guide research programming focused on topics of significant

national interest. The Climate Change Platform was the embryo of this model and became one of them: *Portifólio da Embrapa sobre Mudança Climática* (Embrapa's Climate Change Portfolio) (Figure 1.8), which defined Innovation Challenges to be resolved by research projects. The express objective of the Portfolio was defined as

[... To promote] the adaptation and sustainability of Brazilian agriculture in the face of the challenges posed by climate change, contributing to national and global food security and to control of national greenhouse gas emissions. (Pellegrino et al., 2018, p. 17. Translation ours).

With the Portfolio's strategic focus, the networks established as part of the platform's nationwide projects have evolved and continue to carry out projects that create adaptation and mitigation solutions for agriculture and support public policies. Many of these results will be highlighted as innovation solutions in the chapters of this

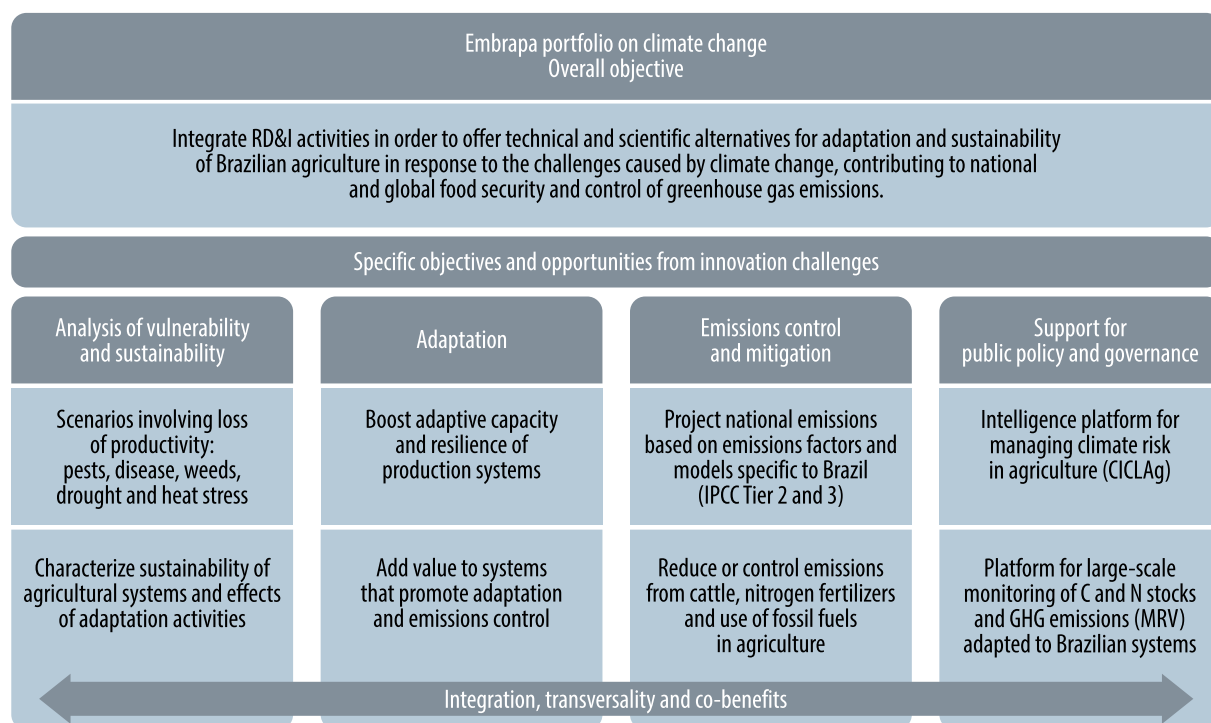


Figure 1.8. Objective and main characteristics of Embrapa's Climate Change Portfolio.

Source: Pellegrino et al. (2018).

book, and (as we shall see below) more can be found on the Embrapa portal, where they are organized according to the main subtopics of climate change and agriculture, as well as in line with the approaches and priorities of COP30 which will be held in Brazil in November 2025.

Technological solutions for the climate

To summarize what we have seen so far, investments in research, development and innovation (RD&I) over recent decades have consolidated Embrapa as a strategic agent in promoting the transition of food systems towards more sustainable, resilient and inclusive models which are in line with contemporary challenges. With this in mind, the company and its partners have promoted the development of technologies and practices that center around adapting to climate change, controlling greenhouse gas (GHG) emissions and conserving, managing and restoring agro-ecosystems. These actions are intended to promote sustainable, healthy and socially inclusive production in different territories.

A systemic approach, combined with strategies to mitigate and control GHG emissions, is indispensable for adapting agriculture to the adverse effects of climate change. Adaptation is necessary not only to respond to the immediate challenges posed by climate change, but also to anticipate future impacts like changes in rainfall patterns, extreme events and rising temperatures. Mitigation, on the other hand, is vital to reduce the carbon footprint of the agricultural sector, with emphasis on sustainable soil and water management and adoption of low-emission agricultural technologies, which encourage more sustainable practices.

Considering these needs, Embrapa focuses its innovative efforts on boosting production

efficiency, developing environmentally sustainable technologies, preserving genetic resources, as well as creating bio-inputs for plant nutrition, biological pest control and adaptation to abiotic stresses (such as drought tolerance). It also invests in research into alternative sources for renewable fuels, improving models and algorithms that increase climate predictability (especially with regard to precipitation and temperature patterns) and developing agricultural systems and practices that strengthen climate resilience and biodiversity conservation.

Another line of activity in Embrapa's RD&I involves advancing the quantification of GHG emissions and removals associated with agricultural practices, taking into account the specific characteristics of production systems in tropical environments. Notable in this context are the development of metrics, protocols and measurement methods at IPCC Tier 3 level, in line with international requirements for the sector.

Embrapa also prioritizes promotion of social innovation, with a focus on transforming food systems to boost food and nutritional security, bolster the adaptation and resilience of production systems and help reduce the carbon footprint of agricultural products. It also values family farming, agroecology, the development of social technologies and appreciation of traditional knowledge, which are fundamental for sustainability and social inclusion in rural areas.

Approaches to address the climate emergency

In order to systematize its contributions related to climate change and its relationship with agriculture within the context of the COP30, Embrapa has adopted six approaches to face the climate emergency (Embrapa, 2025a), which are strategic and priority paths that guide the response of agriculture to climate change in

order to face these challenges intelligently and responsibly (Figure 1.9). Each approach guides the development and application of technologies with a focus on the sustainability, inclusion and resilience of agricultural systems:

Climate adaptation and resilience: adjustments to economic, ecological and social systems to better cope with climate change, reducing potential damage and seizing opportunities. In agriculture, these are innovations, practices, and tools that help farmers deal with the effects of climate change, minimizing negative impacts and ensuring the sustainability of agricultural production. These technologies aim to increase the adaptability of agri-food and forestry systems to variations in temperature and water availability, and also make them more resilient in the face of extreme weather phenomena such as droughts and severe flooding.

Low-carbon agriculture: Practices, methods, and innovations to reduce GHG emissions from agricultural activities, promoting more sustainable production with less environmental impact. The goal is to reduce the agricultural sector's carbon footprint, helping to adapt production systems to the effects of climate change.

Food and nutrition security: Products, processes, practices, and systems that guarantee food production, distribution, availability, and access in order to meet the demands of the population and provide national self-sufficiency for basic foodstuffs, in sufficient and permanent quantities with the nutritional and sanitary quality required to sustain health.

Bioeconomy and the circular economy: This economic model is characterized by low carbon emissions, efficient use of biological resources, and the promotion of social inclusion. It focuses

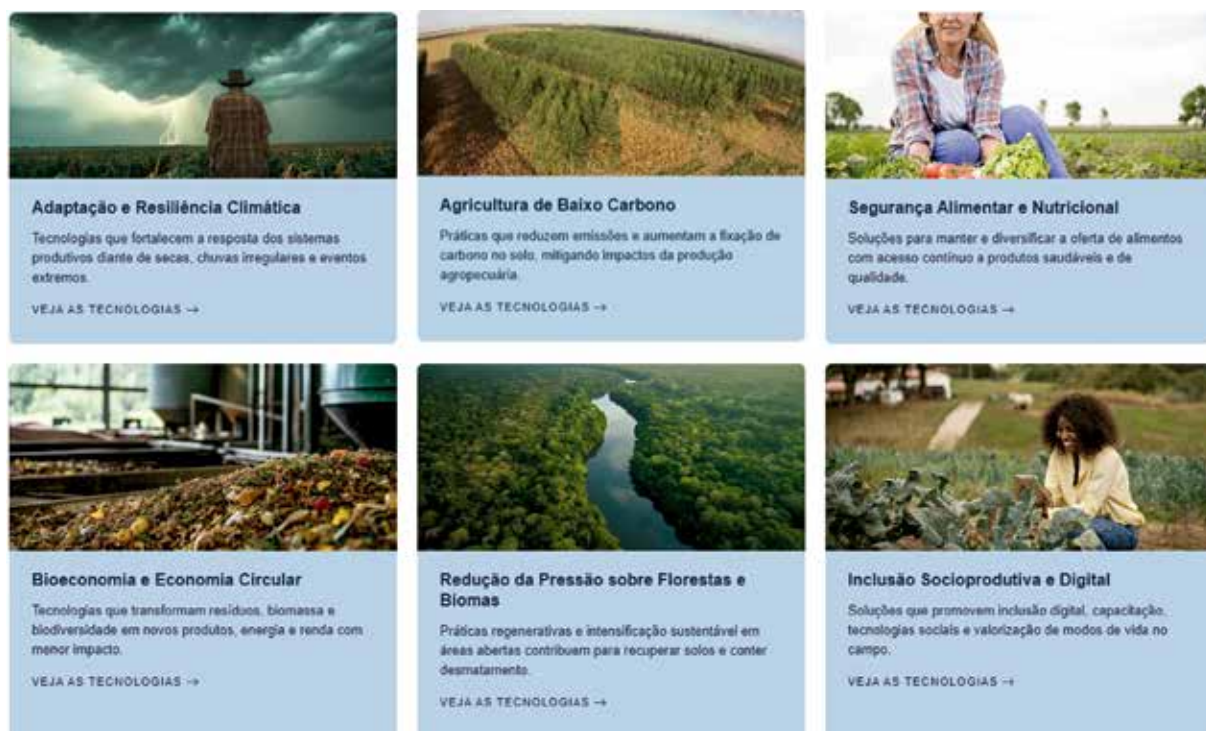


Figure 1.9. Embrapa portal introducing the approaches.

Source: Embrapa (2025a).

on promoting economic growth by generating jobs and income from products of biological origin, in arrangements that also feature efficient management of natural resources and result in the reduction of carbon emissions, pollution and waste generation. The circular economy is specifically based on reusing, repairing, renewing, and recycling materials and products, improving energy efficiency and preserving biodiversity and ecosystem services.

Reducing pressure on forests and biomes:

These technologies and public policies make it socially, economically, and environmentally feasible to boost agricultural production sustainably, based on the premise that standing forests are more valuable than felled ones. The focus is on reconciling productivity and conservation, improving production efficiency in areas already in use, and incentives to plant commercial forests.

Socio-productive and digital inclusion: This broad process is aimed at guaranteeing income and social participation, considering economic, social and cultural aspects. In family farming and other priority groups (such as young people, women, and traditional communities), this involves food sovereignty, sustainability, and valuing knowledge. The main components are access to resources and knowledge, autonomy, and active participation. Digital inclusion is crucial for improving communication, production, and the sharing of knowledge, as well as for expanding production and access to markets and public policies for rural areas.

Contributions to research, development and innovation

In addition to the strategic approaches, Embrapa has brought together 19 topics for Contribuições em Pesquisa, Desenvolvimento e Inovação (Contributions to Research, Development and Innovation) (Embrapa, 2025b) which show how

science can offer concrete answers for tackling climate change (Figure 1.10). They point out specific areas Brazilian science should invest to strengthen resilient agriculture in line with the climate future. Embrapa's contributions linked to the objective of transforming the present and preparing the future of agriculture are:

Systemic approach to the landscape

This approach combines different knowledge areas to create new solutions, looking at the economic, social, and environmental aspects of an area (usually a river basin) in an integrated manner. This means understanding how the different parts of the landscape (nature, economy, society) connect, and planning management that extends beyond individual properties. The goal is to keep natural processes running smoothly, protect biodiversity, guarantee multiple ecosystem services, produce sustainably, attract tourism, generate more income for producers, and promote health for everyone. It also means taking care of the landscape as a whole, considering all its aspects and connections.

Conservation agriculture

This is a set of agricultural practices aimed at sustainable production, with the preservation and restoration of natural resources. These practices include no-till farming, crop rotation, the use of mulch, and integrated pest and disease management, and are intended to increase long-term productivity, improve soil health, reduce erosion, and conserve water while also considering biodiversity and ecosystem services. It also includes a focus on sustainable use of natural resources to ensure availability for future generations.

Bio-inputs

Inputs or products of animal, vegetable, or microbial origin intended for use in practices,

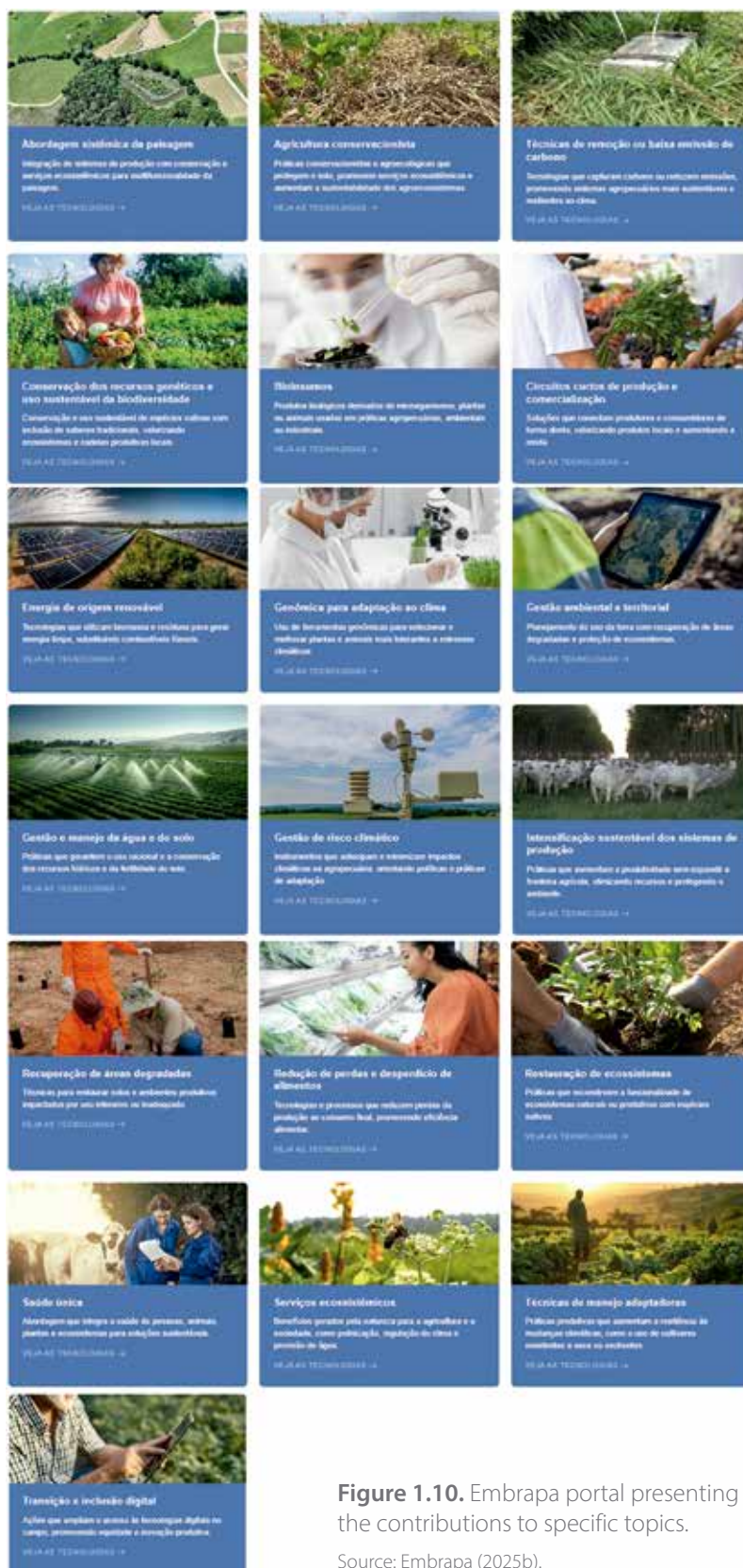


Figure 1.10. Embrapa portal presenting the contributions to specific topics.

Source: Embrapa (2025b).

processes, or technologies with agricultural, environmental, and/or industrial applications.

Short production and marketing circuits

These technologies result in more locally distributed production, reduction, or elimination of intermediaries in the relationship between producers and consumers, as well as decreasing the stages involved in a value chain or steps within a process, reconnecting producers and consumers in a social way, valuing food and non-food products on a local or regional scale, and making it possible to improve income for farmers and quality of life among the population served.

Conservation of genetic resources and sustainable use of biodiversity

Conservation of genetic resources involves different strategies that include *ex situ* (outside natural environments), *in situ* (in natural environments), and on farm methods (preservation and maintenance, generally by family farmers and traditional peoples and communities). Sustainable use of biodiversity is related to the use of natural resources without compromising their genetic and biological diversity, ensuring that the species used are maintained, along with associated species, habitats and the ecological mechanisms and processes involved. These efforts are directly related to socio-productive inclusion, and also involve learning about, collecting, processing, and adding value to products from native biodiversity species (fauna, flora, and microorganisms) while respecting the renewal capacity of ecosystems, including and valuing traditional knowledge in production chains, practicing sustainable soil and water management, and respecting applicable legislation (such as the Brazilian Forest Code). Integrated fire management, agroecological transition, rational use of water, and other

sustainable practices are also important in this context.

Energy from renewable sources

This energy is obtained from wind, solar, hydraulic, geothermal, and various biomass sources that range from agricultural crops to urban waste. Innovation in this field involving agriculture is focused on expanding bioenergy production and implementing technologies to replace traditional fossil fuels. In addition to hydroelectric generation, direct burning of biomass waste for steam generation, for example, these sources also include biofuels (first and second generation ethanol, biodiesel, biogas, and advanced fuels).

Genomics for climate adaptation

These tools and methods for genetic and genome analysis, data integration, and artificial intelligence for understanding and manipulating biological systems and identifying genes, proteins, and metabolic pathways are intended to generate sustainable assets for agriculture and promote the genetic improvement of plants and animals to boost production and expand tolerance to biotic stress (threats to the balance of the ecosystem, from any living being), abiotic stress (threats to the balance of non-living environmental components, such as soil, water, air) and resilience to climate change.

Environmental and territorial management

This area involves land use planning, preservation of protected areas, and remediation of degraded areas, increasing efficient use and improving the health of the soil, contributing to the sustainability of agricultural production. It also involves analyzing all the social, economic, and environmental data about a territory so that it can be properly managed and used sustainably.

Water and soil management

These technologies help plan land use and soil and water management, such as adopting production practices and systems that conserve and protect these water and soil resources in order to guarantee environmental, social, and economic sustainability. They include the supply of drinking water, agricultural irrigation, wastewater treatment, and flood prevention, practices that minimize water waste and contamination. This management also involves practices to preserve and maintain the physical, chemical, and biological quality of the soil to boost its fertility, prevent degradation, and improve its capacity to support productive activities in a sustainable manner that does not negatively affect natural ecosystems.

Climate risk management

This is a set of coordinated actions to reduce the likelihood or magnitude of adverse impacts from climatic events on material goods, society, the ecosystem and agricultural activity. They involve identifying and assessing risk, preventing, addressing, and transferring that risk, as well as monitoring results in terms of reducing loss and damage, maximizing the beneficial impacts and minimizing the negative effects of responses to climate change.

Sustainable intensification of production systems

This is a strategy to improve agricultural, livestock, and industrial practices and reduce pressure on natural areas, optimizing resources and increasing productivity without expanding agricultural frontiers. It involves the use of more efficient technologies, processes, and products, focused on expanding production per area and/or producing in less time, optimizing/rationalizing input use, and emitting less carbon equivalent per unit area and/or for a shorter period of time.

Recovery of degraded areas

This set of techniques and practices is applied to restore areas of land that have been damaged or lost their productive capacity due to agricultural, livestock, or mining activities. This degradation may be caused by various factors that include soil erosion, loss of organic matter, compaction, salinization, pesticide contamination, and deforestation.

Reducing losses and food waste

These technologies and processes aim to minimize losses at every stage of the chain, from production to final consumption. They include adopting good agricultural practices, improved post-harvest handling, proper storage, efficient processing, adequate infrastructure and logistics, effective distribution, and awareness of waste.

Ecosystem restoration

These systems, processes or practices for recovering ecosystems made up of native species (which may or may not also involve exotic species) are intended to re-establish natural ecosystems or permit sustainable economic use of natural resources on rural properties. Examples include integrated crop-livestock-forestry or silvopastoral systems and native species forestry.

One Health

This integrated and unifying approach is intended to sustainably balance and optimize the health of humans, animals, plants and ecosystems. It recognizes that the health of humans, domestic and wild animals, plants and the environment, and all ecosystems are closely linked and interdependent.

Ecosystem services

These are benefits that natural ecosystems provide to humanity, which are indispensable for our survival and essential for socio-economic

development and environmental conservation. Within the context of agriculture, these services play a crucial role in the sustainability of agroecosystems, providing support for sustainable production, regulation of resource use, and environmental preservation. Examples include support services (like maintaining biodiversity and soil formation), provision services (with food or genetic resources), regulation services (regulating air quality or the climate, for example), and cultural services (such as aesthetic values and tourism uses).

Adaptive management techniques

These more efficient agricultural tools, methods, and practices make it possible for production systems to withstand extreme weather events with fewer losses, maintaining or even increasing their productivity. They cover a wide range of management options for production systems, with a focus on expanding adaptation and resilience to the effects of climate change. Examples include: water and soil conservation, mulching with living or dead organic matter, crop rotation, efficient use and/or reuse of water, boosting soil infiltration capacity, diversifying production, protected and/or shaded crops, and developing and adopting varieties and breeds that are more resistant to biological or environmental threats.

Low carbon emission or removal techniques

Environmental carbon removal technologies capture and store carbon from the atmosphere, offsetting emissions from agricultural systems and helping to mitigate climate change. Low-carbon technologies are used to produce food, fiber, and energy while minimizing net emissions of GHG from agricultural systems.

Digital transition and inclusion

Within the context of agriculture, digital transition refers to the incorporation of digital technologies

to transform agricultural production, making it more efficient, sustainable, and competitive. For this transformation to be effective, it is essential to guarantee digital inclusion, democratizing rural producers' access to innovations. This process requires a broad approach that encompasses infrastructure, such as the expanding connectivity in the countryside; capacity building, through training in the use of technologies; accessible solutions, such as simplified applications; and public policies that reduce inequality and promote digitization in the sector.

Solutions for all Brazilian biomes

In each biome, technologies adapted to the local reality help make agricultural production more efficient, resilient and integrated with environmental conservation. The wealth of solutions developed by Embrapa reflects the diversity of Brazil itself (Figure 1.11). In a country that spans a continent and is home to different biomes, climates, soils, crops and forms of production, there is no single solution for tackling climate change. For this reason, Embrapa proposes a varied portfolio of technologies that are adapted to local realities and constructed in dialog with farmers, traditional communities, public managers and the private sector (Embrapa, 2025c). This approach makes it possible for each region to find its own ways to produce sustainably, protect its ecosystems and strengthen resilience in the face of climate challenges.

Figure 1.12 expresses the wide variety of topics and contexts addressed by the solutions presented at Embrapa's technology showcase, with a focus on the 30th United Nations Climate Change Conference (COP30). But for these solutions to achieve the scale and impact desired, efforts must expand not only internally but across the entire innovation ecosystem, including governments, the private sector and civil society. Only with coordinated action will it be possible to promote and strengthen the transition of



Source: Embrapa (2025c).



food systems (production, supply, consumption, and access to healthy food) and production of renewable energy with a low carbon footprint (to replace fossil fuels). It is essential to encourage the adoption of these technologies if we are to build a more sustainable, resilient, and fair agricultural sector.

A look to the future

The current context and the outlook for the future, where it is expected that we will need to produce amid increasingly more severe climate change and more frequent extreme events, while simultaneously reducing pressure on natural biomes that could mitigate the impacts on agriculture and also ensuring food sovereignty and food and nutritional security, involve relevant challenges in terms of:

- **Continuing** to increase the productivity of agricultural crops.
- **Maintaining** the competitiveness of production chains.
- **Knowing, managing**, and **reducing** production risks, especially climate-related risks.
- **Promote** the resilience and adaptation of tropical and national production systems to the effects of climate change.
- **Promote** the social, economic, environmental, and institutional sustainability of production systems.

- **Contribute** to increased healthfulness⁷ and to One Health.
- **Promote** technological advances towards independence from imported inputs and production of food in sufficient quantity and quality, in pursuit of national food sovereignty.
- **Contribute** to the supply of bioenergy, fibers, and other bio-inputs for non-food and industrial production processes.
- **Ensure** socio-productive and digital inclusion in agriculture.

Despite all the contributions Embrapa and its partners have already made, these challenges are unfolding into opportunities and much remains to be done to promote adaptation to climate change and reduce global warming. There are opportunities to move forward on the various themes and approaches presented above, and some specific topics can be highlighted, such as:

- Conservation practices.
- Soil and water management.
- Water storage, efficient use of water and irrigation, water reuse.
- Diversification.
- Crop rotation.
- Protected or shaded crops.
- Managing production risk.
- Urban and peri-urban agriculture.
- Bioeconomy and the circular economy.

⁷ The concept of healthfulness refers to the quality of being healthy or beneficial to health, or to practices that improve or maintain health and quality of life. It is also related to the concept of One Health, which seeks to promote the connection between animal (including human), plant and ecosystem health; in other words, it seeks to promote environmental health as a whole, where the specific health systems of each element of the environmental system are interconnected and interrelated.

- Reducing deforestation and REDD+ (Reducing Emissions from Deforestation and Forest Degradation).
- Ecosystem restoration.
- Biodiversity, microbiomes and bio-inputs.
- Environmental or ecosystem services.
- Conservation of natural resources in the agro-ecosystem.
- Sustainable intensification of agriculture and regenerative agriculture.
- Genetic improvement of cultivars and advanced genomics.
- Agroforestry and integrated systems.
- Adaptation based on communities and their knowledge.
- More distributed and local food production, shortening chains.
- Socio-productive inclusion.
- Logistics infrastructure, storage and regulatory stocks.
- Planning of urban and rural spaces.
- Preparedness and warning systems.

New research platform: structure, topics, and focuses

To plan for this progress in the medium and long term, as well as the new Portfólio Clima, Recursos Naturais e Transformação Ecológica (Climate, Natural Resources and Ecological Transformation Portfolio, Portfólio EcoClima) for managing research programming, Embrapa launched the Embrapa Integra Carbono Initiative in 2024. This initiative consists of:

- A Steering Committee that focuses on issues of governance and corporate strategy, resources and institutional interaction.
- A Standing Committee for the Plataforma sobre Dinâmica de Carbono, Gases de Efeito

Estufa e Adaptação na Agricultura (Platform on Carbon Dynamics, Greenhouse Gases and Adaptation in Agriculture, also known as the CarbGEEAAg Platform)), which is intended to define the planning of research activities in a more corporately integrated manner that involving research networks on the topic and reduces dilution and duplication of efforts through a structuring, long-term approach that permits the development of integrated and complete solutions with greater scope and impact within an environment of collaboration and inter-institutional alliances.

- Thematic subcommittees, which focus on planning and implementing corporate actions with specific focuses.
- Research networks involved in projects on topics related to adaptation and mitigation in agriculture, according to the priorities defined jointly by the Platform's Committees and Subcommittees.

Figure 1.13 shows the Integra Carbono Embrapa Initiative, the relationship between its committees, the hierarchical structure of the platform, and details on the subcommittees and their focuses.

The CarbGEEAAg Platform (Figure 1.13), with constant support from its research, communication, and technology transfer networks and a long-term outlook, has four priority governance areas:

- Updating its research program.
- Management of corporate information and knowledge via a dedicated computing platform.
- Management of the structure and experimental and analytical protocols for long-term experiments.
- Developing quantification methods and techniques at different scales and for different purposes.

From this concept, Embrapa plans to generate more integrated and impactful solutions with the following prioritized approaches:

- Risk monitoring, adaptation, and sustainability of Brazilian agriculture.
- Information management: databases, functionalities, and metrics on the carbon balance in agricultural systems.
- Accessible and scalable techniques and instruments for monitoring field data on carbon and greenhouse gases.
- Carbon balance of Brazil's main agricultural systems, protocols, and representations.
- Carbon accounting and life cycle assessment for Brazilian agricultural products.
- Monitoring and agricultural inventory in the Paris Agreement, challenges in the medium and long term.

These prioritized approaches correspond to specific topics analyzed in more detail in the remaining chapters of this book, which each include an introduction and description of the current panorama surrounding each respective topic. They also present the innovation solutions already offered by Embrapa and partners and the specific future prospects for each one.

Implementation of actions and the generation of impactful results from the solutions that have been developed and made available, with an eye to the future in these respective approaches or themes, is founded on a rationale of continuous and cumulative evolution of the CarbGEEAAg Platform, but always envisioning frequent deliveries throughout this evolutionary process that meet the specific demands of the agricultural sector. Figure 1.14 illustrates this gradual evolution of the platform, expanding and integrating data sets and functionalities (indicators, methods, models, etc.) that will make it possible to produce deliverables that

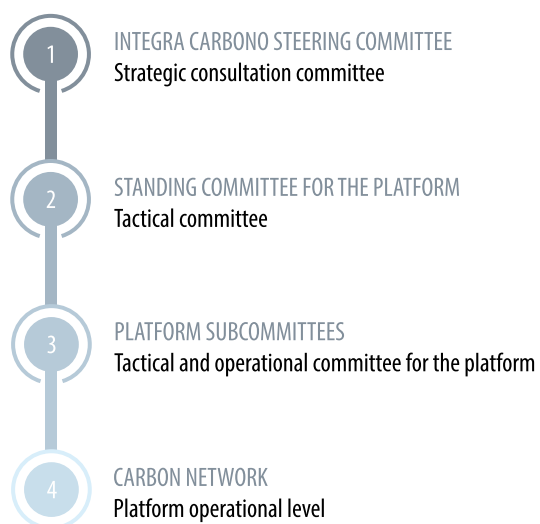
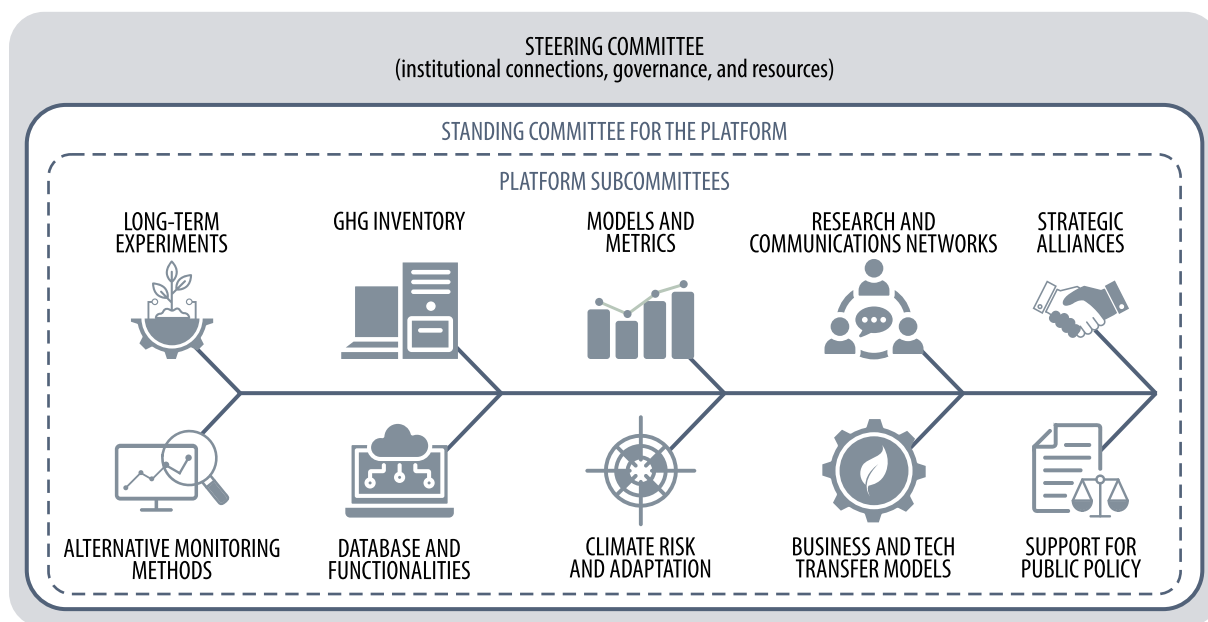


Figure 1.13. Relationship between the Steering Committee, the Standing Committee and the Subcommittees of the Embrapa Platform on Carbon Dynamics, Greenhouse Gases and Adaptation in Agriculture (CarbGEEAaG Platform), as part of the Integra Carbono Embrapa Initiative. Depicted below the box is the hierarchical governance structure of the Integra Carbono Embrapa Initiative.

meet society's demands, strengthening and guaranteeing the sustainability of the process and its evolving structure over the years.

This medium- and long-term vision of the future also envisions a more integrative corporate approach that is structuring, long-term and provides more efficiency and impact through more integrated and consistent innovative solutions to the major challenges in the area of climate change and agriculture, as presented throughout this chapter.

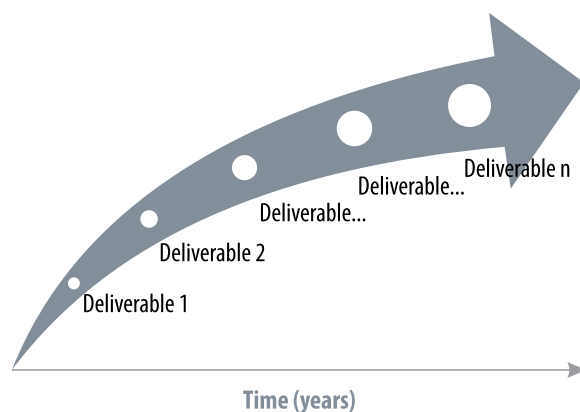


Figure 1.14. Evolutionary and integrative rationale of the CarbGEEAaG Platform, with the production of deliverables over time.

In a nutshell

If we wanted to summarize the main message of this chapter (or even perhaps this book as a whole) into a single sentence, it would go something like this: the development model based on fossil energy sources has caused climate change, and humanity urgently needs science-based alternatives to adopt a sustainable model — which includes agriculture — that make it possible to reverse this process and adapt to current and future scenarios we already see as inevitable, while ensuring food, water, and energy security and the health of the entire planet as a whole.

Yes, that is a long sentence, and probably incomplete, considering the complexity of the issue. But it sums up the rationale we have depicted throughout this chapter, addressing discussions on: the natural energy source that has sustained life on Earth throughout the ages; how the human discovery of fossil energy and our global society's development model has altered this balance, causing climate change; how agriculture and food security are affected by this change; the connections between agriculture and other affected sectors; how international negotiation of agreements and rules on comparable estimates for monitoring the problem takes place, and how these measures are internalized by countries; and finally, what scientific solutions are already available and which ones still need to be found to guarantee the sustainability and integral health of our planet.

We need to move forward as a society that produces knowledge and implements it wisely in order to promote the transition to a development model where there is real balance between economic, social, and environmental aspects, where financial resources do not outweigh natural resources or human and social resources. We need the wisdom to solve the

problems that afflict humanity with responsibility and sincerity. Of course, much remains to be done, but helping expand adoption of the solutions we already have available will make significant progress toward reducing the problems we face, in terms of both adaptation and mitigation.

As this chapter reinforces, solutions exist. What remains can be summed up in two words: take action!

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CHAPTER 2

Risk monitoring, adaptation and sustainability of national agriculture

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Introduction

Climate change scenarios indicate that a 1.5 °C increase in average global temperature is inevitable (Intergovernmental Panel on Climate Change, 2022). In the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), scientists stressed that even with current climate commitments, global warming is likely to exceed 1.5 °C in the coming decades. In addition to rising temperatures, extreme events such as severe droughts, torrential rains, and tropical cyclones are expected to be more frequent; this could lead to a drop in productivity, a reduction in areas suitable for agricultural cultivation, and more frequent occurrence of pests and diseases.

In tropical regions and in scenarios involving intermediate-level and high greenhouse gas (GHG) emissions, global warming is projected to create unprecedented climatic conditions by the middle or end of the twenty-first century, with direct impacts on tropical crop yields. The increasing frequency of extreme weather events in Brazil highlights the urgent need for strategic planning and investment in actions to reduce the vulnerability of productive systems today and ensure a competitive economy in the future.

The impact of climate change on these systems will depend on our ability to implement effective adaptation strategies. Given the elevated vulnerability of the agricultural sector, it is essential to identify



bottlenecks, encourage investments in research and development, and generate data that can support structured and strategic planning. It will be imperative to act quickly and clearly to adopt measures that increase the adaptive capacity of farming systems, strengthening their resilience in the face of adverse climatic conditions.

It is also essential to promote networking, ensuring that the players involved in the decision-making process are well informed and understand the complexity of the challenges. This approach must be transversal, extending beyond the farm gates to encompass transport infrastructure, logistics, energy, and defining indicators for efficiency and performance, creating an environment that fosters the sustainability of national agriculture.

In this sense, Brazilian agricultural research has made progress in addressing climate change by developing and implementing adaptation measures that promote sustainable production. This research focuses on identifying information and knowledge gaps, developing regional models and climate risk scenarios, sustainable use of natural resources, reducing pressure on biomes, protecting biodiversity, recovering degraded areas, and restoring ecosystems to support the sustainability of production systems. New production strategies and technological solutions compatible with future climate risk scenarios have also been developed, and include support for genetic research, conservation of water and soil resources, training, and management of ecosystem services.

The climate risks inherent in the tropical environment require Brazil to take a strategic stance, ensuring that technological development, dialog, and training for decision makers take place in a coordinated and integrated manner. Adapting to the impacts of climate change is strategic for economic development, and crucial to maintaining the country's competitiveness. This will require a multifunctional approach

characterized by production that promotes conservation of soil, water, biodiversity, and ecosystem processes while also taking into account unique local and regional characteristics. These activities should also help control GHG emissions by implementing regenerative farming systems (Brazil, 2023).

Priority strategies include genetic improvement to develop cultivars that are tolerant to abiotic and biotic stressors resulting from climate change, improving the environment through systems that reduce internal temperature, protection against heavy rainfall, and increasing water availability. Examples of these strategies include protected cultivation (such as indoor crops, for example), rational irrigation management, the use of mulch or ground cover (using plastic or plant waste), water reuse and storage, as well as non-soil cultivation systems such as hydroponics and aeroponics.

The first step towards adaptation is understanding the vulnerability and risks of production systems, in terms of both the current climate and the climate projected for the future. This can include identifying the best time to plant crops and the occurrence of plant health problems, for example. Based on the risk analysis, preventive measures for the short, medium, and long term will need to be implemented. These measures should include the integration of technologies, such as combined use of cultivars that are tolerant to rising temperatures and drought, soil conservation practices (like mulching, crop rotation and no-till farming), rational water and input management, use of growth-promoting microorganisms and biological control agents, and crop diversification and integration.

Practices that prioritize ecosystem conservation help address climate change. The coordinated adoption of these technologies can enhance the adaptive capacity of production systems, promoting food security and sustainability (Figure 2.1).

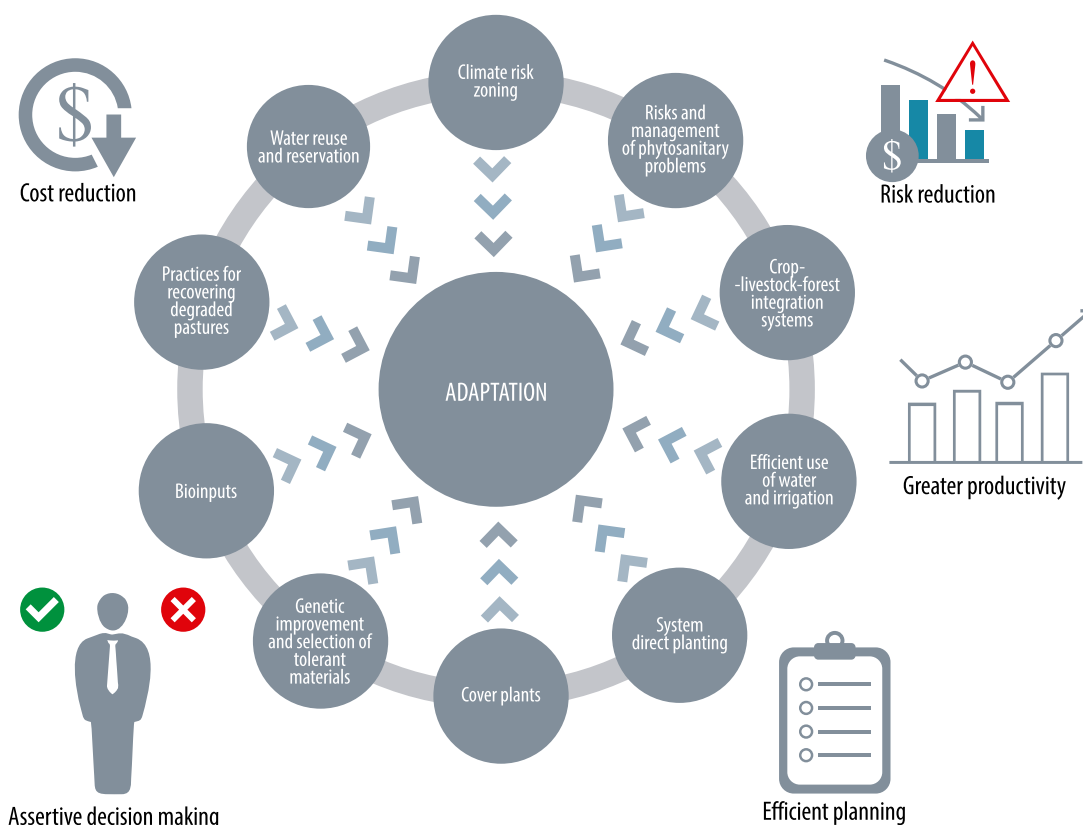


Figure 2.1. Advantages of implementing adaptation measures for agricultural production.

However, the adaptation process is ongoing, and the proposed solutions will need to be implemented and improved within local and regional contexts and also depending on the specific crop, which reinforces the role of agricultural research.

Current outlook - climate risk in agriculture

The exposure of crops to climate risks is an inherent reality of agriculture itself, and it is widely accepted that the agricultural sector is among the most vulnerable to the current and future impacts of climate change. This characteristic already demands that the sector make significant investments in training and

understanding the challenges inherent not only to natural climate variability, but also the transformations climate change has already brought about in rural dynamics, which will continue to have significant impacts on the agricultural sector over the coming decades. For this reason, knowledge and technologies must be incorporated into daily practice in order to live with these risks and reduce their effects.

Over three decades (from 1979 to 2008), Ray et al. (2015) studied the influence of interannual variability in climatic conditions on production in the main regions around the world that produce corn (*Zea mays*), rice (*Oryza sativa*), wheat (*Triticum aestivum*), and soybeans (*Glycine max*). Although these authors found that not all regions were significantly influenced by the climate, in some areas more than 60% of production

variability was explained by variations in weather conditions from year to year. This relationship of cause (climate variability) and effect (production variation) was clearly seen in the vast majority of regions producing corn (70%), rice (53%), wheat (79%), and soybeans (67%). These areas accounted for 78% of the world's corn production, 52% of rice, 75% of wheat, and 67% of soybeans. The study showed that in most productive regions, climate variability is responsible for 32% to 39% of variation in the production of these crops.

As climate change intensifies (and is already altering patterns and negatively impacting life in rural areas), it is becoming increasingly difficult to plan effective strategies to deal with climate risks. This difficulty is particularly acute in communities that have a poor understanding of the dimensions and complexities associated with the process of climate change, which in turn leads to low adoption of technologies and practices that could reduce risks. Visible results of climate uncertainty include increased unpredictability, higher agricultural insurance costs, economic, social, and environmental losses, and food insecurity on various scales. This scenario highlights the strategic importance of scientific development and the role of academia in broad dialog with society. Building bridges of understanding between science and society about the challenges and impacts of climate change is a fundamental strategy for adaptation in the agricultural sector. The decision to prioritize strategic and structuring investments in long-term research is becoming increasingly necessary as a way to anticipate risks and produce appropriate technologies in response.

In Brazil, the impact of climate change on the agricultural sector has been studied for decades, with particular attention from 2018 onwards (Fiorini et al., 2024). The main climate variables

considered in these studies were air temperature and rainfall. While this research most frequently focused on corn, soy, and sugarcane (*Saccharum officinarum*), some analyses also involved crops such as cocoa (*Theobroma cacao*), rice, beans (*Phaseolus vulgaris*), wheat, and cassava (*Manihot esculenta*). According to a study by Fiorini et al. (2024), 67% of the investigations these authors evaluated reported negative impacts on production systems as a result of climate change, 15% reported both negative and positive impacts, 11% reported neutrality, and only 7% reported exclusively positive impacts.

According to data from the Central Bank of Brazil, the main climate risk factor in agriculture is drought, which was responsible for most of the economic losses covered by the Programa de Garantia da Atividade Agropecuária (Agricultural Activity Guarantee Program, PROAGRO) between 2013 and 2021. In the case of soybeans and corn, for example, drought-related losses accounted for 86.8% and 75% of the compensation paid out by the program, respectively. On the other hand, drought is less relevant for wheat (16%), compared to excessive rain (37%) and frost (39.4%) (Banco Central do Brasil, 2025).

For livestock operations, the most critical problem is the seasonality of forage production, characterized by inconsistent supply of food throughout the year. During the wet season, environmental conditions are favorable and food is plentiful, but during the dry season, decreases in temperature, light, and rainfall cause forage to be scarce, leading to a drop in production and reproduction rates for livestock (Oliveira, 2024a). This situation is further aggravated by the degradation of pastures, which facilitates water loss and erosion due to the presence of exposed soil, and more recently by extreme weather events resulting from climate change, such as longer droughts and frosts during times of food scarcity (Oliveira et al., 2022a).

The future scenarios for pasture in Brazil up to 2070 show that, although there may be an increase in productivity due to the rise in temperature, there will also be variations in production between years and seasons. The seasonality of forage production will be accentuated, with higher production in the wet season and less production during the dry season — especially in soils with low water storage capacity, such as sandy (Pezzopane et al., 2019) and degraded soils. These scenarios make forage planning essential.

Although Brazil has 12% of the planet's fresh surface water (Agência Nacional de Águas e Saneamento Básico, 2022), this availability is unevenly distributed throughout the country, where some regions have water surpluses and others suffer chronic shortages, such as the Semi-Arid region.

In general, climate change projections indicate increases of up to 1 mm day⁻¹ in reference evapotranspiration (ET₀), mainly in the North, Northeast and Midwest regions (Monteiro et al., 2024a). These increases demonstrate greater pressure on the water balance, and a tendency toward more intense water deficiency in agriculture. Population growth is also likely to place pressure on the multiple uses of water resources, complicating the situation even further.

Reports by Coutinho and Cataldi (2023) show trends of reduced water availability between 2020 and 2100, as well as an increase in the magnitude and frequency of extreme events in the river basins of the Parnaíba and São Francisco Rivers in the Northeast, and the Iguaçu and Uruguai Rivers in the South. Projections based on IPCC scenarios also point to a greater intensity of these events in scenarios characterized by greater use of energy, fossil fuels, and other demands related to the current development model.

Specifically in the Cerrado biome, projections indicate that less water will be stored in reservoirs in the future, resulting in greater risks of supply failure. This is especially for smaller reservoirs, where increased evaporation is expected to reduce water availability during the dry season, with losses of up to 10.4% in the most severe IPCC scenarios (Althoff et al., 2020). Furthermore, average monthly groundwater recharge could decrease by 21% in the intermediate scenario and by 29.4% in the most severe scenario, which would compromise water availability and accentuate conflicts between users, especially during the dry season (Cambraia Neto et al., 2021).

In Northeastern Brazil, according to Medeiros and Oliveira (2022), climate models project more dry days throughout the year in all scenarios, increasing drought in the region, especially in the most severe IPCC scenario. The models also suggest greater intensity of rainfall in summer, in other words, the same volume of rainfall occurring during fewer events, which could make management difficult and negatively impact crop yields. At the same time, the flow of water into reservoirs (and, in turn, the availability of water for irrigated agriculture and other users) depends on this rainfall. For this reason, water security in the Brazilian Northeast could depend heavily on the storage capacity and management of water resources in the region.

Moreover, increased evapotranspiration caused by higher temperatures due to climate change is expected to generate greater demand for water for agricultural crops. In this way, climate change and increased demand for food are becoming major factors that place pressure on water resources, especially in irrigated agriculture. This makes it essential to implement public policies focused on adaptive measures that promote water security and the resilience of production systems.

Solutions

Agricultural climate risk zoning

Given the importance of minimizing agricultural production losses in Brazil as the result of climatic factors, in the 1990s Embrapa and the Ministry of Agriculture and Livestock (MAPA) began the Projeto de Redução de Riscos Climáticos (Climate Risk Reduction Project) (Rosseti, 1998), which was the starting point for the consolidation of the Agricultural Climate Risk Zoning (ZARC) technology. The goal of ZARC is to assess risk to agricultural crops based on agrometeorological elements, and estimate the probability that the climatic requirements of agricultural crops will be met in different regions and planting seasons.

The ZARC project is implemented with technical and scientific support from Embrapa, and maintained and updated by MAPA. The results of the ZARC studies constitute official data and guidelines for parties involved in the agricultural sector (such as producers, credit and rural insurance institutions, and public authorities) when making decisions about practices that minimize climate risk for agricultural production. In this way, ZARC serves to strongly encourage good agricultural practices that result in greater resilience in food, fiber, and energy production systems.

The data produced by ZARC is formalized through ordinances published by MAPA and is used as indicators for drawing up contracts under PROAGRO, in the Programa de Subvenção ao Prêmio do Seguro Rural (Rural Insurance Premium Subsidy Program, PSR), as well as for insurance and rural credit operations (Monteiro et al., 2024b; Banco Central do Brasil, 2025). These activities are linked to the National Agricultural Policy (Law 8.171/1991). In 2024, BRL 22.48 billion was involved in PROAGRO operations, according to the Central Bank of Brazil's Data Matrix (Banco Central do Brasil, 2025). As for the PSR,

the amount insured in 2023 exceeded BRL 51.6 billion (Brasil, 2024).

The ZARC tool uses historical meteorological series data over approximately 30 years from approximately 3,500 observation points distributed throughout the country (Monteiro et al., 2024b). This data is applied to simulation models to generate water balances for each zoned agricultural crop. The results are then compared with the specific needs of each crop, which when not met can compromise growth and production.

The simulation process is carried out for 10-day cycles (with 36 10-day cycles each year), considering the ripening cycles of the cultivars and different soil types. Using data about the water balance and air temperature, the frequency of occurrence for weather conditions that are favorable or unfavorable for the specific crop over the historical series can be calculated. According to Monteiro et al. (2024a), the following adverse weather events can be taken into account: periods of drought during sensitive phases like flowering and grain filling; frosts; excessive rainfall that impedes mechanized harvesting or affects grain quality; excess humidity that favors fungal diseases; and very high temperatures that cause flowers to abort or fruit to fall off in the early stages of formation.

Based on these simulations, ZARC presents climatic risk as its final result, for specific spaces (regions or municipalities) and times (planting and cultivation seasons), for each combination of crop, cycle length, and soil class, making it possible to identify locations and times of year with greater chances of success, in other words lower chances of poorer harvests (Monteiro et al., 2024b).

As an instrument for assessing climate risk, ZARC is a dynamic tool from a temporal and methodological point of view, and is constantly being improved through updates in scientific

and technical support by the research project team. One such refinement is the improved definition in the concept of water available for crops (Monteiro et al., 2022), where there are now six levels of soil water availability rather than the three levels previously adopted.

Another innovation being developed is the ZARC Management Levels (ZARC NM), which incorporate criteria that take into account the producer's soil management quality (Debiasi et al., 2022). This concept is based on the premise that adopting conservation practices significantly boosts the resilience of production systems, in turn reducing their vulnerability to adverse weather events.

Furthermore, within the context of global climate change, the ZARC project team is carrying out initial analyses of future climate risks based on IPCC projections. These studies use the climate scenarios developed in the 6th phase of the Coupled Model Intercomparison Project (CMIP6)¹ and are being applied to ZARC's simulation models to assess the impacts of projected changes on climate risk for agricultural crops over time.

Although ZARC is primarily intended to be a tool for adapting to climate change, its recommendations also encourage more sustainable agricultural practices, such as the use of conservation systems and efficient soil and water management, which can result in indirect contributions to mitigation of GHG emissions.

Risks and management of plant health problems

The new geography of crops as a result of climate change will also have an impact on the occurrence of pests and diseases. This is a worldwide concern, since 20 to 40% of global agricultural production is lost due to plant health

problems (Intergovernmental Panel on Climate Change, 2021). In Brazil, studies of risks resulting from fungi, bacteria, nematodes, and viruses have been carried out on 32 crops of economic importance. These analyses indicate that among the 304 interactions between plants and microorganisms evaluated, 46% of agricultural diseases tend to exhibit an increased risk of climatic favorability, which can make them more severe (Angelotti et al., 2024). This is an important warning sign, since management strategies will need to be monitored and even modified if they are to be effective in controlling pathogens.

These risks have been assessed through modeling and field experimentation (Angelotti et al., 2017; Araujo et al., 2019; Bisonard et al., 2020). The most recent advances highlight regionalized analyses, as in the case of grapevine diseases, where the risk of occurrence may increase depending on the producing region, since in Brazil grapevines are grown in both temperate and tropical climate regions (Angelotti et al., 2017). Another relevant example is black sigatoka, a significant leaf-spot disease in bananas. It is estimated that the risk of infection has increased by 44.2% in the banana-producing areas of Latin America and the Caribbean (Bebber, 2019).

Virus-borne diseases also deserve special attention, since rising temperatures can have a direct impact on vectors such as aphids, accelerating their life cycles and expanding their populations, which in turn favors virus spread.

Based on the risk analyses, and considering interactions between pathogens and the new climate scenario, adaptation strategies will need to be adopted to protect the health of crops. The main measures include: a) incorporating preventive practices to reduce the spread of pests and pathogens; b) strengthening plant health surveillance; c) using cultivars that are tolerant or resistant to diseases; d) developing new chemical or biochemical molecules;

¹ Available at: <https://wcrp-cmip.org>.

e) selecting biological control agents adapted to higher air temperatures; f) promoting diversified cultivation systems; g) integrating different management technologies; and h) using epidemic forecasting and warning models (Angelotti et al., 2024).

Integrated crop-livestock-forest systems

Integrated crop-livestock-forest (ICLF) systems represent a sustainable production strategy that incorporates agricultural, animal and/or forestry activities carried out in the same area using intercropping, succession or rotation. The goal of ICLF is to diversify production and amplify synergistic effects between the components of the agroecosystem in four types of production systems: crop-livestock (agropastoral), crop-forest (agrosilviculture), livestock-forest (silvipastoral), and crop-livestock-forest (agrosilvipastoral).

An estimated 11.5 million hectares of areas incorporated ICLF systems during the 2015/2016 harvest season, with the highest concentrations in the states of Mato Grosso do Sul, Mato Grosso, Rio Grande do Sul, Minas Gerais, Goiás and the Federal District, São Paulo, and Santa Catarina. Considering an average annual growth rate of 0.96 million hectares in the period from 2005 to 2015, it is estimated that in 2020 in Brazil there were roughly 16.27 million hectares using some form of ICLF (Polidoro et al., 2021).

Incorporating ICLF is part of the actions of the Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura (Sectoral Plan for Mitigation and Adaptation to Climate Change to Establish a Low Carbon Economy in Agriculture) also known as the ABC Plan), which was established in 2012 and revised in 2020, when it was renamed the Plano Setorial para Adaptação à Mudança do Clima e Baixa Emissão de Carbono na Agropecuária,

com vistas ao Desenvolvimento Sustentável (2020–2030) (Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture, with a view to Sustainable Development [(2020–2030)] now known as the ABC+ Plan (Brasil 2023). The ABC+ Plan envisions an expansion of 9 million hectares in areas utilizing ICLF in Brazil by 2030, contributing to an increase in sustainable agricultural practices, expansion of farming to ensure global food demands, and reduction in GHG emissions without the need to convert new areas.

The expansion of cultivated areas using the various ICLF modalities provides Brazil with a model for sustainable land use, with less environmental impact and greater diversification of income. This result stems from the system's inherent characteristics, such as diversification and increased production per area, provision of environmental services, reduced GHG emissions and increased carbon sequestration, as well as the land-saving effect, which supports environmental preservation (Oliveira et al., 2024b). The positive characteristics of these production systems determine the high potential for expanding their adoption in the country, mainly by incorporating unproductive areas, including large tracts of degraded pastureland.

Several studies have shown that integrated crop-livestock systems boost organic matter content in the soil and favor the formation of aggregates through root activity, especially with the presence of tropical grasses. These factors improve overall soil quality due to crop-pasture rotation cycles, increasing water retention in the soil and providing production systems with greater resilience during unseasonal warm periods (known in Brazil as *veranicos*) (Salton et al., 2014; Bieluczyk et al., 2024). In addition, when these systems are well managed and utilize appropriate animal stocking levels, they maintain productivity of various crops and are essential for strengthening food security in an increasingly

challenging climatic environment (Nunes et al., 2021b). Income diversification also helps to reduce climate risks and market fluctuations (Vinholis et al., 2021).

Including trees in production systems (Figure 2.2), in silvopastoral or agrosilvopastoral systems, is also a strategy for adapting to climate change, since trees alter the growing environment, which is reflected in improved thermal comfort rates for the animals (Magalhães et al., 2020). Pezzopane et al. (2019) found that silvipastoral systems using

eucalyptus or native species were able to delay the onset of animal heat stress by an average of up to 2.2 °C, compared to systems without trees.

Efficient water use and irrigation

Within the context of climate change, efficient use of water and modernization of irrigation are fundamental adaptation strategies to ensure the resilience and sustainability of Brazilian agriculture.



Photos: José Ricardo Pezzopane

Figure 2.2. Brachiaria grass (*Uruçloa* spp.) pasture as part of an integrated crop-livestock system, after soybean farming (A) and a silvopastoral system with Brachiaria grass and eucalyptus pasture (B).

One technological solution for sustainably increasing production while using the same productive areas is irrigation. According to the *Atlas Irrigação [Irrigation Atlas]* published by Brazil's National Agency for Water and Basic Sanitation (Agência Nacional de Águas e Saneamento Básico, 2021), Brazil irrigated a total of 8.2 million hectares in 2019. This same document estimated the potential for increasing irrigated area in the country to 55.85 million hectares; the areas with the most favorable conditions for irrigated agriculture accounted for 13.69 million hectares, or 24.5% of the total potential area that could also be irrigated. This data shows how little irrigation technology has been implemented in Brazil, and above all, its potential reach and impact, given the prospects for increasing adoption in Brazilian agricultural production systems.

But the increase in irrigated area naturally implies greater use of water resources, and potentially more conflicts over use of these resources, especially in regions where water is scarce. In this sense, solutions are needed for efficient water use, especially considering the potential impacts of climate change on the availability of water resources.

The sensitivity analysis of irrigation water demand to improved application efficiency (especially for low-efficiency systems) shows a greater potential for demand reduction than the projected increases caused by the effects of climate change. This type of response indicates that system efficiency is an important operational factor to be considered in adaptation strategies for irrigated agriculture (Maia et al., 2016). Gains in irrigation efficiency may be able to compensate projected increases in water demand as the result of climate change, as reported by Gondim et al. (2008, 2012, 2018).

Better water management, along with the use of appropriate inputs and agronomic practices, could result in greater production with the same

levels of water consumption. Higher irrigation water productivity (kg/m^3) increases “real water savings,” permitting greater production with the same amount of evapotranspiration (Van Opstal et al., 2021).

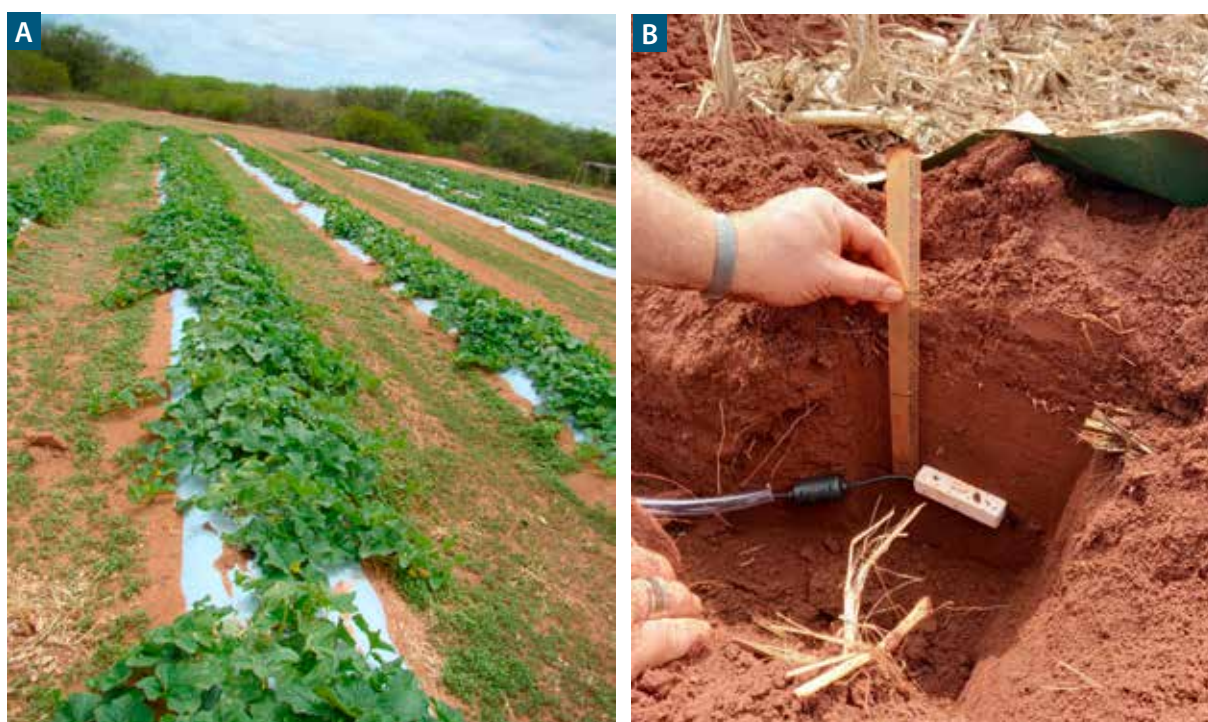
Management options are available for farmers to improve water productivity while also protecting their yields, developing strategies to optimize the use of irrigation water within their production areas. These strategies include:

- Preferential use of localized irrigation (drip or micro-sprinkler systems), as well as periodic evaluation of water application uniformity, with preventive maintenance of the system to repair potential leaks or clogs to attain uniform distribution. Drip irrigation is another technology that can significantly boost efficient water use. Research indicates that controlled, timely application of water through drip irrigation increases forage production and especially water use efficiency during dry seasons, leading to more effective use of available land, fertilizers, and water (Jha et al., 2016).
- Application of mulch or no-till planting (also known as direct planting or stubble cultivation) (Figure 2.3) also reduces losses from evaporation, since the mulch, ground cover or vegetation from the previous crop protects the soil from the sun, boosting water retention and availability in the soil.
- Applying white plastic ground cover (Figure 2.4) also retains water in the soil surface and reduces evaporation losses. In a study investigating various types of ground covers in watermelon cultivation, Saraiva et al. (2017) concluded that white plastic increased water retention and fruit quality compared to soil that was uncovered.
- Use of soil moisture sensors (Figure 2.4). There are various types of these sensors on the market; water tensiometers are the easiest



Photos: Sebastião José de Araújo

Figure 2.3. Melon (A) and beans (B) as no tillage using crop residue cover.



Photos: Fabrícia da Silva Ramos

Figure 2.4. White plastic ground cover to reduce evaporation losses (A). TDR soil moisture sensor (B).

to use. Time-domain reflectometry (TDR) sensors are more expensive, but are useful for monitoring large areas and measuring moisture levels that are beyond the range of tensiometers. These sensors make it possible to assess the amount of water in the soil that is available to plants in order to determine when and how much water to apply.

- Controlled deficit irrigation. In this strategy, irrigation is used during the crop's drought-sensitive growth stages. Outside of these periods, irrigation is limited or even unnecessary, when rain provides a minimal supply of water. Water restriction is limited to drought-tolerant species, at less critical phenological stages. Although this inevitably

results in water stress for the plants and consequent loss of production, water productivity (kg/m^3) can actually increase. Raeisi et al. (2019) reported an increase in physical water productivity in wheat, from $0.37 \text{ kg}/\text{m}^3$ (with full irrigation) to $0.56 \text{ kg}/\text{m}^3$ when deficit irrigation (50% deficit) was used.

- Application of soil conditioners such as biochar (Figure 2.5) or hydrogel to increase water retention in the root zone in sandy soils. Hydrogels are hydroabsorbent polymers that help retain water in the soil, while biochar is a carbonized material resulting from incomplete combustion of organic material which holds water in its pores. Biochar has been applied to improve soil fertility, mitigate the effects of climate change by increasing carbon sequestration in the soil, reduce GHG emissions, and increase water retention capacity in sandy soil. Gondim et al. (2020) reported reduced water consumption in cashew seedlings during the first year after

application of cashew wood biochar and hydrogel, from 120 L per plant per year to 70 L per plant per year and 55 L per plant per year, respectively. In irrigated adult dwarf cashew plants, Gondim et al. (2024) observed a reduction from 14,098 L per plant per year to 11,962 L per plant per year, with maximum water productivity of $1.2 \text{ kg}/\text{m}^3$ for nuts (control treatment: $0.93 \text{ kg}/\text{m}^3$) and $8.9 \text{ kg}/\text{m}^3$ for peduncles (control treatment: $8.1 \text{ kg}/\text{m}^3$).

- Development, availability and adoption of mobile apps by producers to disseminate information on reference evapotranspiration in real time and irrigation time able to meet crop water needs could evolve with the use of the Internet of Things (IoT) and artificial intelligence capable of monitoring and predicting the climatic, physical, chemical and hydrological characteristics of a field, while also detecting, locating and predicting the biological characteristics of crops (Bounajra et al., 2024).
- Efficient use of fertilizers is also associated with water use efficiency when nutrient loss through leaching is avoided. This also helps maintain crop productivity, which is reflected in water productivity, since crop yield increase means production with less water.
- Water reuse is a way to use nutrients from effluents and also avoid discharging them into water bodies or groundwater and polluting. Miranda et al. (2008) showed that the grain yield obtained from the use of shrimp effluent was similar to that obtained with river water when N-P-K equivalent to 100% of the recommended dose for the crop was used in fertilization. When a dose of N-P-K equivalent to 75% of the recommendation for the rice crop was used, the use of effluent in irrigation gave a higher grain yield compared to irrigation using river water.

Photo: Rubens Somsol Gondim



Figure 2.5. Application of biochar as a soil conditioner in cashew tree planting holes.

Faced with the challenges posed by climate change, the combination of technologies, good agronomy practices, and monitoring tools will be decisive in increasing the efficiency of water use in irrigated agriculture. Investments in training, public policies and technological innovation must happen together in order to guarantee water and food security in the country.

No-till planting

Agriculture faces growing challenges posed by climate change that demand innovative technological mitigation and adaptation solutions to ensure the sustainability of food production. No-till or direct planting is one such strategic climate adaptation technology for sustainable agriculture. In Brazil, the no-till technique was first adopted in 1972 to control water erosion (Telles et al., 2013). The minimum requirements of no-till planting are not plowing the soil, crop rotation, and keeping the soil covered with living and dead plants.

After five decades of research, observations, and practical experience with the sustainable use and management of soil, water and biodiversity, no-till planting has incorporated a series of technological solutions and innovations that make it viable and continually improving. No-till planting is consequently one of the basic technologies that makes Brazilian agriculture a benchmark in tropical and subtropical agriculture in all three dimensions of sustainability: environmental, economic, and social.

Planting without tilling the soil is emerging as a key strategy to mitigate environmental impacts and increase the resilience of production systems. In Brazil in 2023, approximately 33.03 million of the 58.72 million hectares cultivated with temporary crops (MapBiomas, 2025) used no-till planting (Federação Brasileira do Sistema Plantio Direto, 2021); this made significant contributions to soil and water conservation and carbon sequestration, in turn fostering low-

carbon agriculture. These benefits result from no-till planting because such efforts in Brazil respect important precepts for tropical and subtropical agriculture such as terracing, crop diversification, intercropping, use of summer grasses with larger amounts of root phytomass, as well as harvesting and sowing processes that keep the soil simultaneously covered with mulch and living plants as long as possible (Reichert et al., 2016; Nunes et al., 2021a; Denardin, 2024).

The no-till system has also been adapted for growing vegetables due to its ability to sequester carbon, reduce surface and subsurface soil temperatures, promote efficient water use, and protect against erosion (Marouelli et al., 2006; Lima et al., 2018).

Finally, an important study by Rocha and Gonçalves (2024) evaluated the role of no-till systems in land use decisions in Brazilian municipalities. These authors found evidence that no-till systems not only offer sustainability to Brazilian agriculture by recovering degraded areas and increasing crop productivity, but also have an indirect positive effect on environmental conservation by encouraging preservation of natural areas.

Along these lines, Embrapa is addressing many innovation challenges related to no-till planting in order to develop original solutions for both adapting to and mitigating climate change that extend into the countryside and are positively received by the various agricultural value chains (which include production of grains, fruit, animal protein, energy, and fibers and integrate farmers, industry, and consumers on a national and global scale).

Cover crops

The cultivation of cover crops is one of the most promising technological solutions for sequestering carbon in the soil, cycling nutrients, adding nitrogen through biological fixation,

enriching soil life and consequently adding quality to the soil-plant system through species diversification, and also considering benefits to the root system and crop productivity. It is important to highlight the benefits of using cover crops in integrated management of invasive plants, diseases, and insects that occur in crops. Diversifying cropping systems with the use of cover crops is an essential strategy for suppressing invasive plants, for example, reducing general competition between species and the dominance of herbicide-resistant species (Leskovšek et al., 2025). There are many examples of integrated management to interrupt or mitigate pest and disease cycles through the use of cover crops, such as nematodes (Mbiri et al., 2024) and *Fusarium* fungi (Kadziene et al., 2020).

In Brazil's subtropical and tropical conditions, there is a wide variety of well-adapted cover crop species (Figure 2.6) that can be grown in systems to produce grain (Bayera et al., 2016; Ensinas et al., 2016; Schulman et al., 2025), cotton (Lopes et al., 2021), vegetables, and fruit (Giongo et al., 2020; Deus et al., 2022; Silva et al., 2024). Studies focus on integrating chemical, physical, and biological indicators to improve health in the soil-plant-atmosphere system and the multifunctionality of agroecosystems to increase

Over the past decade, simultaneous cultivation of different botanical families (known as cover crop mixes, plant cocktails or green manure mixes) has contributed to concepts of multifunctionality, environmental services, and regenerative agriculture by positively influencing different chemical, physical and biological processes, leading to higher crop yields and resilience to adverse climatic conditions. One example is a study by Silva et al. (2024) conducted in Brazil's Semi-Arid region, where different species of cover crops were cultivated either preceding or in combination with irrigated melons in no-till and conventional cultivation systems, as part of a long-term experiment. This research found that

soil management practices and simultaneous cultivation of oilseeds, grasses, and legumes as part of no-till planting were able to bring soil carbon stocks in the 0–20 cm layer to the same levels as those found under vegetation in the Caatinga biome.

Future-oriented actions link the use of cover crop species with provisioning, support, and regulation services that can be provided by agroecosystems with a multifunctional character. For example, Deus et al. (2022) identified species for single-crop and intercropped planting that are best suited to specific services, according to the needs of each agricultural growing environment. For instance, these authors noted that the number of species in a consortium is related to the production of aerial and root biomass and accumulation of carbon and nitrogen in the soil, which makes agroecosystems better suited to provide provisioning and regulating services.

Genetic improvement and selection of tolerant materials

Measures to adapt to climate change include selecting genotypes that are tolerant to resulting stressors. This is a strategic activity for national competitiveness, since it can provide crops with characteristics that not only help avoid production decreases, but can even boost productivity by integrating management techniques we have already described in this chapter, making it possible to meet growing demand for food quantity and quality for a growing world population. In Brazil, notable research has involved adapted genotypes of soybeans, corn, sorghum, millet, cassava, cowpeas, rice, lettuce, and potatoes (Caranhato et al., 2022; Oliveira et al., 2022a, 2022b; Barros et al., 2023, 2024; Lima et al., 2024a; Silva et al., 2024).

In classical plant breeding, genotypes are selected after pre-improvement, in the

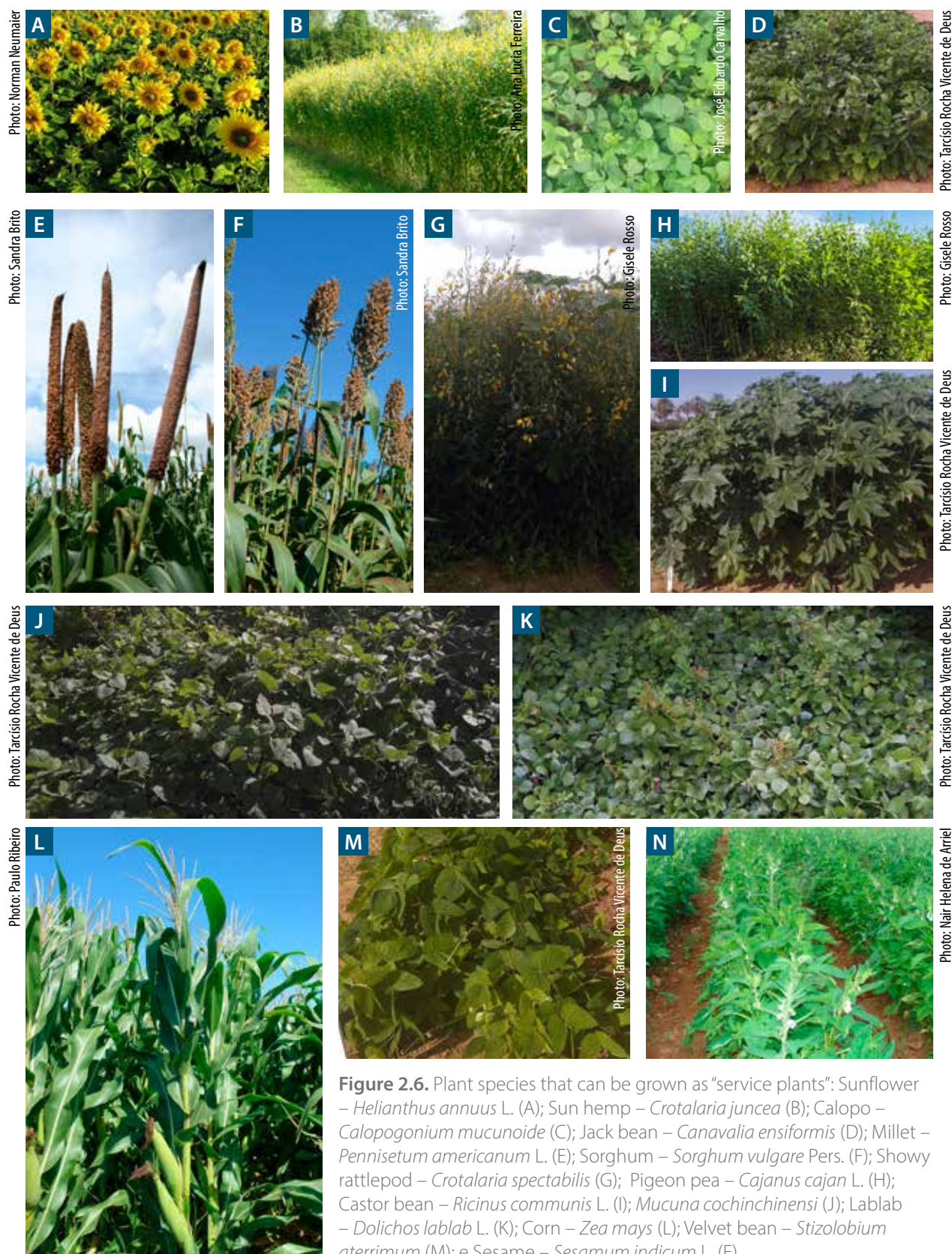


Figure 2.6. Plant species that can be grown as "service plants": Sunflower – *Helianthus annuus* L. (A); Sun hemp – *Crotalaria juncea* (B); Calopo – *Calopogonium mucunoides* (C); Jack bean – *Canavalia ensiformis* (D); Millet – *Pennisetum americanum* L. (E); Sorghum – *Sorghum vulgare* Pers. (F); Showy rattlepod – *Crotalaria spectabilis* (G); Pigeon pea – *Cajanus cajan* L. (H); Castor bean – *Ricinus communis* L. (I); Mucuna – *Mucuna cochinchinensis* (J); Lablab – *Dolichos lablab* L. (K); Corn – *Zea mays* (L); Velvet bean – *Stizolobium aterrimum* (M); e Sesame – *Sesamum indicum* L. (N).

evaluation and management stages of the breeding program. Tolerant materials are selected by analyzing genetic, physiological, biochemical, and production parameters (Barros et al., 2021). The responses of this genetic material are part of characterization, and can be analyzed in appropriate environments such as growth chambers that simulate predicted climate change scenarios, or in contrasting field conditions (Barros et al., 2023, 2024). Under stress, plant cells activate genes involved in the response to higher temperature and drought, helping to prevent cell damage. Characterization of the genes expressed in response to abiotic stressors is essential to develop plants that are tolerant to climate change, and also makes it possible to identify molecular targets for genetic improvement programs and agricultural biotechnology.

Right now, high-performance phenotyping platforms using techniques to capture images of plants at different stages of growth and development are helping to advance genetic improvement (Brito et al., 2023). Additionally, evolution in genomic protocols resulting from genetic sequencing of plants has provided dozens of genes that influence important agronomic characteristics, including those related to yield components and tolerance to biotic and abiotic stressors (Caranhato et al., 2022; Barros et al., 2024). Biotechnology makes it possible to insert specific genes with desirable characteristics into new cultivars, using transgenic techniques. One example is the introduction of the *AtAREB1* gene into elite soybean germplasm to increase drought tolerance (Caranhato et al., 2022).

New advanced genomics technologies involving CRISPR/Cas9 are also being developed to improve and accelerate plant breeding efforts. Genome editing via CRISPR (clustered regularly interspaced short palindromic repeats) involves using a single guide RNA (sgRNA) to break

the double strand of DNA at a predetermined location and alter a specific genetic sequence. In Brazil, corn breeding is already using this tool to increase production, quality, nutritional value, and tolerance to biotic and abiotic stressors (Oliveira et al., 2022b).

Another new approach that is gaining ground in scientific research and complements traditional genetic improvement is the use of microbiomes (Camargo et al., 2023). The goal is essentially to study and take advantage of the communities of microorganisms that live in plants, animals, or the soil to help improve desirable characteristics like disease resistance, tolerance to environmental stress, faster growth, or greater productivity. This technique consists of inoculating plants with specific microbiomes to increase their resistance to heat, drought, or pests, without directly altering the plant's DNA. In this way, the use of microbiomes combined with genetic improvement represents an innovative frontier for making agriculture more efficient and sustainable.

Bioinputs

The first concerns about harm caused by the use of chemical pesticides in agriculture emerged in the 1950s. In Brazil, attention to the environmental impacts of agriculture grew in the 1980s, when secondary consequences began to be studied more systematically. At that time, it became clear that intensive use of these products had the potential to cause negative impacts, both inside and outside agroecosystems.

Within the agroecosystem, excessive use of pesticides increases dependency due to biological imbalances, which include elimination of natural enemies and antagonists, the resurgence of pests, resistance to active ingredients, and the emergence of new plant health problems caused by eliminating the agents responsible for natural biological control.

Outside agroecosystems, chemical pesticides have the potential to harm consumer health, and also contaminate the soil, water and air.

Within this context, biological controls help restore biodiversity and develop sustainable agriculture, generating benefits for the environment and plant health. They also offer significant health benefits for farmers, consumers, and livestock, while the sustainability tripod is improved by the economic and social advantages of biological controls which are associated with efficiency and benefits to environmental and public health.

To encourage the use of biological products in Brazilian agriculture, the Ministry of Agriculture and Livestock (MAPA) created the Bioinsumos (BioInputs) Program through Decree 10375 of 2020 (Brazil, 2020), “to expand and strengthen the use of bioinputs in the country to benefit the agricultural sector.” Here, the term “bioinputs” is defined as:

[...] a product, process or technology of plant, animal or microbial origin, intended for use in the production, storage, and processing of agricultural products, aquatic production systems or planted forests, which positively interferes with the growth, development, and response mechanism of animals, plants, microorganisms, and derived substances, and which interacts with physical, chemical, and biological products and processes. (Translation ours)

In this way, the incentive is not just limited to the use of biological controls, but covers the use of biological products in Brazilian agriculture. This program has been widely debated by society, in discussions which have helped expand the use of biological products.

Biological controls are used as effective solutions to health problems (such as diseases, pests, and weeds) in agriculture, livestock farming, and public health. They can be classified into

four types: natural, conservation, classical, and augmentative.

In natural biological control of agricultural pests and diseases, the populations of these organisms are kept in balance by the action of naturally occurring antagonists and natural enemies, without any human intervention.

In biological control involving a conservation strategy, human activities are intended to protect, stimulate, and preserve beneficial agents, favoring the natural increase of their populations.

Classical biological control is based on collecting natural enemies in areas where they occur (usually in the region where the pest, pathogen, or weeds occurs) and releasing them in places where you want to increase the number of biocontrol agents, which can result in a permanent population.

Finally, augmentative biological control is when antagonists, insect pathogens, parasitoids, and predators are applied to a crop in large numbers. This method is most commonly known to farmers, since it is based on application of biocontrol agents (fungi, bacteria, oomycetes, viruses, mycoviruses, bacteriophages, predators, and parasitoids) that are available on the market (Bueno et al., 2020).

The fungi *Beauveria bassiana*, *Isaria fumosorosea*, *Metarhizium anisopliae*, *Paecilomyces* sp., and *Trichoderma* spp., as well as the bacteria *Bacillus amyloliquefaciens*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus methylotrophicus*, and *Bacillus thuringiensis*, are the most widely marketed biological control agents in Brazil. In terms of treated area, the most notable are *Trichoderma* and *Beauveria*. *Bacillus* species, which are used to control nematodes and plant diseases in various crops, are most important when considering all of the biological controls available in Brazil (Medeiros; Bettiol, 2023).

In addition to pest and disease control, bioinputs also involve the use of organisms for purposes that include promoting plant growth, protecting against abiotic stressors (such as water, salinization, and higher temperatures), efficient use of nitrogen, solubilizing and release of nutrients, and nitrogen fixing (undoubtedly the most common use of organisms in the country).

As for mitigating the effects of drought on crops, various products have been launched on the Brazilian market. One example is *Bacillus aryabhattai*: the first commercial product involving this species (Auras) was developed in a partnership between Embrapa Environment and the NOAA company, which is currently distributed by various companies in the sector. This microorganism, isolated from Caatinga soils, has the ability to hydrate roots and influence plant physiology, allowing plants to respond better to water deficits. *Bacillus aryabhattai* also stimulates development of the root system, boosting water absorption (May et al., 2021; Fuga et al., 2023).

Another important group of microorganisms that are not yet widely utilized in Brazil are mycorrhizal fungi. Besides helping to absorb phosphorus, these organisms can induce resistance to plant pathogens, and products based on these fungi will need to be developed for the country's main agricultural crops.

Ectomycorrhizae are mainly used in tree species, since many are dependent on them, especially plants in the genus *Pinus*. Most ectomycorrhizal fungi are basidiomycetes (such as *Pisolithus*, *Thelephora*, and *Boletus*), and can be produced *in vitro*, which simplifies production. These mycorrhizae not only contribute to plant nutrition, but can also protect against pests and diseases.

Another important group are arbuscular mycorrhizae, which are present in most plant

species. This symbiosis is extremely important in agriculture, since it promotes the absorption and exchange of nutrients while also helping to protect against diseases and nematodes. The most significant challenge hindering commercial utilization of this group is large-scale production, which limits the market.

Meanwhile, soybeans are one of the main crops responsible for growth in the use of bioinputs in Brazil. In addition to biological nitrogen fixation, biological control of pests and diseases is also used on this crop on a large scale. In this way, part of the history of the use of biological products in Brazilian agriculture is intertwined with the history of soybean cultivation in Brazil. Biological nitrogen fixation and biological control of the soybean caterpillar may be the two most significant examples. We also cannot ignore biological control of white mold (caused by *Sclerotinia sclerotiorum*) in soybeans using products derived from *Trichoderma* and *Bacillus* (Faria et al., 2022).

The most important group of biofertilizers uses bacteria for biological nitrogen fixation. Species from the genera *Bradyrhizobium*, *Rhizobium*, and *Azospirillum* are the most widely used in Brazil, with a mixture of *Bradyrhizobium elkanii* and *Bradyrhizobium japonicum* strains used in soybean cultivation (Hungria et al., 2006, 2015, 2020). In addition to these, the use of *Azospirillum brasilense* has also grown significantly in recent years (Hungria et al., 2015; Santos et al., 2021). These microorganisms not only reduce costs for farmers (who no longer need to use nitrogen fertilizers on their soybean crop), but also considerably reduce the environmental impacts that would reduce from the use of mineral nitrogen, especially considering the data from Rockström et al. (2009). This information is extremely important, considering that the soybean harvest in 2023/2024 totaled approximately 46 million hectares (Embrapa Soja, 2025).

During the 2020/2021 harvest, the use rate for biofertilizers in Brazilian soybean cultivation reached 80%, while *Bradyrhizobium* + *Azospirillum* co-inoculation was 26% (Globalferti, 2021). For the 2020/2021 harvest, these figures represent an area of 30.821 million hectares of soybeans where biofertilizers were used and 10.017 million hectares involving co-inoculation, for a total of 38.526 million hectares, and indicate the success of this technology developed in Brazil. Considering the cultivated area for the 2020/2021 harvest, the savings exceeded USD 17.8 billion (Hungria; Nogueira, 2022). These numbers clearly show not only the importance of using biofertilizers in soybean cultivation, but also the importance of research and development of bioinputs for the country.

These bacteria, which replace the use of nitrogen fertilizers for many plants, represent a very significant clean and sustainable technology, especially for soybean cultivation in Brazil, since *Bradyrhizobium* bacteria can fix up to 300 kg/ha (Peoples et al., 1995). However, other species such as *Azospirillum amazonense*, *Azospirillum halopraeferans*, *Azospirillum lipoferum*, *Herbaspirillum seropedicae*, and *Acetobacter diazotrophicus* (Döbereiner, 1990) are also recognized as nitrogen fixers.

Practices for recovering degraded pastures

Measures to adapt to climate change consist of bolstering the resilience of production systems, expanding diversification of animal and plant species, and reducing risks, as well as co-benefits arising from GHG mitigation (Oliveira et al., 2023, 2024a, 2024b; Pezzopane et al., 2024). In pasture systems, adaptation measures are related to forage plant management, genetic improvement with new cultivars and varieties, soil management, forage planning, and new arrangements in production systems (Thornton; Herrero, 2014; Braga; Ramos, 2017). Most of these techniques are part of the pasture recovery process, which is based on three basic principles: proper forage plant management, restoring soil fertility, and adopting soil conservation practices (Oliveira et al., 2003, 2005, 2007a, 2007b).

Recovering a pasture consists of using the existing plant population and employing techniques that promote remediation of the degraded area, and can be carried out in various ways that include direct pasture recovery, co-planting with legumes, or using the various integrated crop-livestock systems described in the literature (Oliveira et al., 2003; 2005, 2007a, 2007b, 2024a) (Figure 2.7).

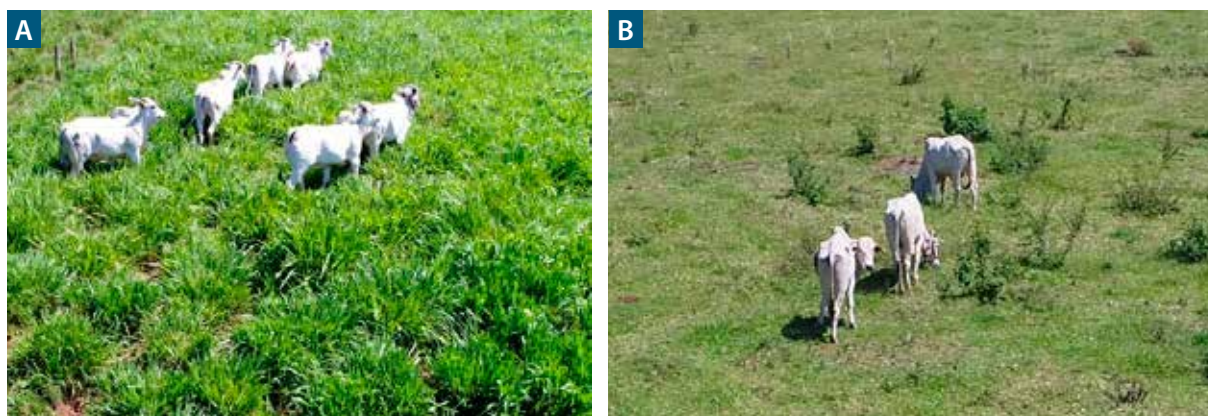


Figure 2.7. Appearance of pasture and animals in recovered pastures (A) compared to degraded pastures (B).

The need for pasture recovery began to gain visibility after good outcomes in production systems and efforts beginning in the 1990s by the research and development (R&D) sector, and these efforts were included within the context of the 2012 ABC Plan and the 2020 ABC+ Plan (Brazil, 2023). Today, considering these various techniques, the Programa Nacional de Conversão de Pastagens Degradadas em Sistemas de Produção Agropecuários e Florestais Sustentáveis (National Program for Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems) (Brazil, 2024) proposes intensification of beef cattle farming and includes pasture recovery.

Intensifying pasture management by soil correction with lime and improving soil fertility increases forage production during the dry season of the year, offering a greater quantity of food during this period of intense drought. Findings obtained by Pasquini Neto et al. (2024, 2025), in experiments involving recovery and intensification of pastures in Southeastern Brazil, demonstrated an increase in dry matter production during the fall/winter. During this time, the degraded pastures (DP0) produced 3.07 t of dry matter per hectare, while the recovered, corrected and fertilized pastures produced 4.57 t/ha with 200 kg of nitrogen (N) per hectare per year (RP200), 9.45 t/ha with 400 kg of N per hectare per year (RP400), and 10.44 t/ha when irrigated and reseeded in autumn/winter and fertilized with 600 kg of N per hectare per year (IR600).

The increase in forage production in the fall/winter was reflected in increases in weight gain (0.02, 0.54, 0.42, and 0.82 kg/day) and animal stocking rates (2.15, 2.68, 3.77, and 4.99 animal units per hectare), which in turn raised productivity (kg of live weight per hectare) in the production systems, obtaining 119, 362, 444, and 700 kg/ha for the DP0, RP200, RP400, and IR 600 systems, respectively.

Drought resilience in intensified pasture management is even reflected in carcass yields, rising from 53.3% in a degraded system to 55.8% in intensified treatments, increasing meat productivity per hectare (Oliveira et al., 2018).

Increasing the diversity of forage species is one alternative for adapting to drought (Oliveira et al., 2024b; Pezzopane et al., 2024). Intercropping pigeon peas with tropical grasses for pasture recovery is a good drought adaptation strategy, since this legume has a deep, pivoting root system and is very drought tolerant (Oliveira, 2022; Pezzopane et al., 2024). It maintains forage production and green leaf retention during the dry season, especially the BRS Mandarin cultivar. In very sandy soils with low water retention, this mix provided a better nutritional composition for diet and average daily weight gain per animal for females during the dry season (0.29 kg/day), using only ordinary mineral supplementation, which was much higher than the weight gain (0.03 kg/day) obtained in pastures fertilized with 200 kg N per hectare and additional protein mineral supplementation. An increase in animal stocking and final weight for the heifers was also seen (Oliveira, 2022).

From an agronomy point of view, Pezzopane et al. (2024) also observed significant benefits. Pasture intercropped with pigeon peas produced 18.5 tons of dry matter per hectare per year: 7.5 tons/ha from *Brachiaria* grass and 11 tons/ha from the pigeon peas. In comparison, reclaimed pastures fertilized with 200 kg of N per hectare per year produced 11.1 t/ha of *Brachiaria*, while degraded pastures produced only 5.6 t/ha of dry matter. Because the animals prefer to consume the pigeon pea plants during the dry season, this volume of forage represents an important food stock for this period. Furthermore, the presence of the pigeon peas boosted the crude protein content of the *Brachiaria* grass from 5.8 to 7.1%, considering the average for the dry and rainy seasons.

Intercropping with pigeon peas is just one example of various options available for mixing forage species in pastures that offer potential for climate change adaptation (Furtado et al., 2023) (Figure 2.8). Selection of forage species must take into account complementary characteristics that increase the resilience of pastures to abiotic stressors (Oliveira et al., 2023), such as the potential to produce and maintain forage quality in the dry season (Valle et al., 2017). Another factor to consider is better use of water through hydraulic lifting, the ability of grasses or legumes with deeper root systems to recycle water and improve the water environment in the forage canopy (Pezzopane et al., 2024).

Integrated crop-livestock production methods such as silvopastoral, agropastoral, and agrosilvopastoral systems have also been adopted for pasture recovery. These integrated systems involve diversification, rotation, consortium, or succession of agricultural or livestock activities harmoniously within a rural property as part of one single system in such a way that creates benefits for all components (Alvarenga et al., 2006). Integrated systems that are adopted to remediate pastures also provide greater resilience to abiotic stressors, providing fodder during the dry season after crops have been harvested, for example, from pasture sown together with grain crops such as soybeans, corn

and rice, and offer superior quality, especially in terms of protein content (Brunetti et al., 2022). The main benefits are increased productivity, diversified production, less vulnerability to climatic effects, improved fertility, physical, and biological quality of the soil, reduction of pests and diseases, and erosion control (Alvarenga et al., 2006), in addition to issues related to improved environment such as more thermal comfort for animals when the integrated system involves trees (Pezzopane et al., 2019; Magalhães et al., 2020).

Water reuse and storage

Reuse of wastewater can be understood as an innovative and sustainable practice that involves its deliberate use in diverse human processes such as agricultural production (Lopes Sobrinho et al., 2024).

Although Brazil has no national-level legislation on the reuse of wastewater in agriculture, some states have legal standards regulating this practice, such as the states of Rio Grande do Sul (2020) (CONSEMA Resolution 419/2020), Ceará (2017) (COEMA Resolution 02/2017), Bahia (2017) (CONERH Resolution 75/2010), and Minas Gerais (2020) (CERH Normative Deliberation 65/2020). International instruments from organizations such as the World Health



Photos: Patrícia Perondi Ancho Oliveira

Figure 2.8. Appearance of pasture recovered by consortium planting with pigeon peas (A) compared to the degraded pasture (B) at the start of the dry season.

Organization (World Health Organization, 2006) and the European Parliament (2020) (Regulation 741/2020) can also help define water quality parameters for agricultural use. Irrigated agriculture is Brazil's largest user of water, consuming 50% of all the water distributed in the country (Agência Nacional de Águas e Saneamento Básico, 2024). In this context, the Política Nacional de Recursos Hídricos (National Water Resources Policy, PNRH) (Law 9433/1997, Brasil 1997), establishes the priority uses of water resources as human supply and animal watering, which requires agriculture to look for alternatives for water use in irrigation. The agricultural reuse of wastewater has been shown to be a viable alternative to mitigate the impacts of extreme drought events resulting from global climate change (Moura et al., 2020) and is safe as long as indicated water quality parameters are respected, providing not only water but also nutrients for agricultural crops (Lopes et al., 2024). Embrapa has developed alternatives for rural sanitation and wastewater reuse, with projects such as the Fossa Séptica Biodigestora (Biodigester Septic Tank) (Galindo et al., 2019), Jardim Filtrante (Filter Garden) (Leonel et al., 2013), Bioágua Familiar (Family Biowater) (Melo et al., 2023), and the Sistema ReAqua (ReAqua System) (Lima et al., 2024a), as well as products to improve the quality of post-treatment wastewater for irrigation (Ferreira et al., 2024).

Meanwhile, water storage can be understood as the construction and management of structures such as reservoirs, cisterns and dams (Formiga-Johnsson; Britto, 2020). In Brazil, water collection and storage systems for food production in gardens, orchards, fodder crops, and animal watering contribute to water security for populations, such as in the Semi-Arid region (Oliveira et al., 2016; Castro et al., 2024). Examples of technologies developed by Embrapa include Barragens Subterrâneas (Underground Dams) (Melo et al., 2011), Cisternas Domiciliares

(Household Cisterns) (2007), and Barraginhas (Caranhato et al., 2022). These are social technologies that have transformed sustainable development in the Semi-Arid region, since they permit significant accumulation of water during the rainy season for use as water storage during periods of drought.

Pollination as an ecosystem service

Ecosystem services also play a strategic role in combating climate change. These services can be defined as benefits that the environment provides to human beings, and which are essential for maintaining life on Earth. But the human population is not the only one that benefits from these services, since ecological processes ensure the survival of different species by providing food, water, shelter and other necessities.

The main ecosystem service provided by bees is pollination, which significantly boosts reproduction in many wild and cultivated plants. Pollination is fundamental to ensuring genetic variability, species survival, and ecosystem balance, with direct and indirect implications for the ability of natural and human systems to adapt to the effects of climate change.

Pollination is responsible for around 75% of global crop production, with an estimated economic value of between USD 235 and 577 billion each year (Potts et al., 2016). An analysis of 141 crops in Brazil showed that the economic contribution of pollinators to agricultural production amounts to approximately USD 12 billion, half of which is attributed to soybeans (Giannini et al., 2015).

Soy is an autogamous and cleistogamous plant, meaning that most flowers self-pollinate, often before they even open completely. This implies that soybean production does not depend on the presence of pollinators, but studies show that the presence of pollinators (especially

bees) in soybean crops increases yields by up to 18.24%, depending on the variety used, the environmental conditions, and the cultivation practices utilized on the crop (Gazzoni; Barateiro, 2023). Soybean flower pollination increases the number of beans in the pods, and reduces the number of seedless pods or pods with only one bean. The weight of the bean also increases with pollination, guaranteeing greater productivity in the same area without the need to apply more inputs (Gazzoni; Barateiro, 2023).

In Brazil, bees are the largest group of pollinators and represent 66.3% of the animal species that pollinate as an ecosystem service (BPBES, 2019). However, expanding the supply of pollinators in crops from both managed and wild bees requires the adoption of management practices that reduce the negative impacts of agriculture on these populations so the producer can benefit from the ecosystem service these insects provide.

One of the most commonly recommended bee-friendly practices for attracting and conserving bees near crops is creating more heterogeneous and diverse landscapes, along with protecting and restoring nearby natural areas. Suggestions include taking advantage of borders, spaces between rows, fence lines, and other spaces to plant preferably native species that can provide a diversified and staggered diet for bees, as well as sites to build their hives. Replacing monoculture fields with areas containing greater agricultural biodiversity boosts the resilience of the system, and together with increased natural biodiversity around the crop areas, promotes sustainable ecological processes like pollination via bees.

These areas will also be used as nesting sites and refuges for other insects that are beneficial to agriculture, such as ladybugs and praying mantises that help control pests, and coprophagous beetles and some flies that decompose organic matter and improve soil health. Expanding agricultural and natural biodiversity benefits the ecosystem service of

pollination, but also boosts the resilience of the farming system, with consequences for increased production.

Adopting sustainable agricultural practices, including transitioning to agroecology, also helps preserve bees, and for this reason no-till planting is recommended to avoid excessive disturbance of the soil. Grading and plowing not only compromise soil health and related ecosystem services, but also decrease the quantity and variety of food sources and nesting sites for bees that nest in the ground (Potts et al., 2016). Excessive overgrazing and lack of ground cover should also be avoided, especially in the off-season. These practices contribute to soil degradation and reduce the availability of food, shelter, and nesting sites that are essential for maintaining pollinator populations.

Another practice to avoid is using fire to prepare the soil. This conventional agricultural practice is extremely harmful to bees and other pollinators. Fire directly destroys habitats, reducing the quantity and variety of food and nesting sources. Agricultural management without the use of fire, on the other hand, minimizes wildfires, protects ecosystems, and helps preserve both soils and pollinators (Coutinho et al., 2020; Potts et al., 2016).

The flow of bees to pollinate crops can also be increased by introducing hives, nests and colonies, especially native stingless bees and *Apis mellifera*. Starting to raise bees or encouraging the installation of beekeeping and honey production near crops are other strategies that can be used to mitigate the pollinator deficit and increase the number of effective pollinators for crops.

Renting colonies is one alternative that is already widely used in Brazil to increase the flow of bees, in crops that include melons, coffee, and apples. Even soybeans can benefit from the installation of well-distributed beehives nearby. Research indicates that in addition to productivity, the

presence of beehives benefits the germination rate in soybean seed production, and hives are considered an interesting input for maximizing production of this crop (Wolditsadik et al., 2023).

Faced with the multiple challenges posed by climate change, it is essential to recognize the strategic role of functional biodiversity in processes for adapting production systems. Within this context, bees are a key element in ensuring resilience of agricultural systems, as the main pollinators of most food crops and native ecosystems. Pollination by managed and wild bees not only contributes to increased productivity and food quality, but also strengthens the ecological stability of agricultural landscapes in the face of extreme climatic events.

Preserving natural habitats, diversifying crops, and reducing pesticide use are fundamental practices, not only for protecting bees, but also for building more robust and adaptable agroecological systems. For this reason, climate change adaptation strategies must integrate pollinator conservation across the board as an essential component of food security, ecosystem health, and rural sustainability. These strategies act in synergy to influence other ecosystem services, making the agricultural system even more resilient and adapted to climate emergencies. Valuing and protecting bees is consequently an investment in building a more balanced and productive climate future.

Future prospects

As the global climate alters, changes in temperature patterns, precipitation, and seasonal cycles directly affect agricultural production. Fragmentation and simplification of agricultural landscapes is a limiting factor, and can contribute to the vulnerability of tropical agriculture. However, the future does not necessarily involve collapse: there are promising

scenarios, especially if integrated biodiversity conservation and sustainable land management strategies are adopted. Creating ecological corridors, encouraging agroecology, promoting diversified agriculture, and reducing the use of pesticides are all measures that can strengthen integrated landscape management, restoring its capacity to provide services. The IPCC Land Use Change report published in 2019² points out that landscape management measures are particularly strategic in tropical regions, where protection of forest cover will have the positive effect of increasing environmental cooling as a result of natural evapotranspiration. Increased evapotranspiration preserves the occurrence of cooler days during the growing season and has a protective effect, reducing the amplitude of extreme weather events related to heat.

For this reason, given the current climate and the potential scenarios related to climate change, it is essential to improve domestic governance on the subject of climate change, particularly by strengthening dialog and investing in education in order to reduce misinformation and broaden decision makers' understanding of the complex challenges associated with current and future climate change processes. Prioritizing investments in strategic research with a focus on reducing uncertainties and generating data in order to reduce information gaps are critical tools needed for a well-informed decision making process, and will consequently reduce the risk of diminished competitiveness in tropical production systems.

Food security is a major challenge, and tropical production systems today are (and in the future will be even more) exposed to the challenges posed by climate change. This means there must be continuous improvement and integration of technologies, like those presented in this chapter, to guarantee the resilience of agricultural

² Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2022/11/SRCCL_SPM.pdf

systems responsible for producing food, fiber, and energy. Science-based agriculture is the best tool for facing the challenges posed by rising average atmospheric temperatures, changes in rainfall patterns, and resulting impacts on food sovereignty.

Given the complexity of tropical agriculture, technological advances through large-scale phenotyping, genotyping, and gene editing will be key points for crop improvement. Other tools, such as the use of artificial intelligence (AI) to automate projection and mapping of future agricultural scenarios, risks, and vulnerabilities, could support research in order to expand the capacity of crops to adapt to the climate.

The adoption of integrated adaptation measures for biodiversity maintenance and conservation can offer economic opportunities, through payments for environmental services and sustainable certifications. However, investments in research and monitoring will be essential, since the adaptation process is continuous and the proposed solutions will need to be carried out and improved within local and regional contexts, and also specifically for each crop.

For this reason, future prospects for increasing the adaptive capacity of agriculture depend on scientific research and innovation actions that will guide and support public policies for sustainable tropical agriculture. The integration of measures aimed at conserving the environment is not just an ecological necessity, but a pillar for a more resilient, productive, and sustainable agricultural future in the face of climate uncertainty.

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Agricultural Climate Risk Zoning

A powerful differentiator in **risk management** for Brazilian agriculture

Zoneamento Agrícola de Risco Climático (Agricultural Climate Risk Zoning, or ZARC) is a tool to support agricultural policy instruments and risk management in agriculture. It is essentially a study to minimize the exposure of public resources to risks related to climatic phenomena, since it makes it possible to identify the best planting time for agricultural crops in each municipality and in different soil texture classes and crop cycles.

It is implemented through the publication of ordinances by the Ministry of Agriculture and Livestock (MAPA)'s Agricultural Policy Secretariat (SPA). These ordinances indicate planting dates linked to 20%, 30%, and 40% failure risk, based on historical weather conditions. New ordinances are published every year, involving both crops and locations that have already been zoned and new arrangements of crops and locations. During the 2024/2025 harvesting year, these ordinances covered a total of 55 crops in all 26 Brazilian states, as well as the Federal District.

Today, after more than 20 years in operation, ZARC is an important indicator of the use of resources provided for in Brazil's National Agricultural Policy (Law 8,171/1991), since it supports decisions made in some programs and provides guidance for credit and agricultural insurance. In order to qualify for the Programa de Garantia da Atividade Agropecuária (Agricultural Activity Guarantee Program, PROAGRO) and the Prêmio do Seguro Rural (Rural Insurance Premium Subsidy, PSR), producers must follow the ZARC recommendations. In the case of the Programa

de Garantia da Atividade Agropecuária da Agricultura Familiar (Family Farming Activity Guarantee Program, PROAGRO Mais), it is not required but still strongly recommended. In this way, ZARC intermediates and provides technical security for these relationships and promotes mutual benefits, since it helps minimize risks on both sides of the operation, for both financing agents and borrowers.

ZARC also has direct effects on productivity and income generation, with consequent improvement in the competitiveness of Brazilian agriculture. Furthermore, because its use is restricted to priority areas for agricultural use, it avoids conflicts with the conservation of natural resources, making it an essential tool for economic sustainability.

From a conservative perspective, it is estimated that Brazilian production has increased by at least 20% since ZARC came into use. Using this reference for further calculation, another estimate considers that, during the 2006–2024 period, the gross production value (GPV) of areas contracted with PSR aid reached a positive impact of BRL 187.95 billion. For PROAGRO, the estimated impact of ZARC from 2013 to 2024 is around BRL 83.66 billion. Together, these two gains are very significant, amounting to BRL 271.61 billion, and result from ZARC's very low operational costs. In the profitability analysis for the 1994–2023 period, ZARC demonstrated a benefit/cost ratio of 285.69, indicating that the project is highly viable: every investment of BRL 1.00 yields a return of BRL 285.69.

Photo: Gessi Ceccon



Corn-brachiaria consortium: in the event of frost, corn protects the brachiaria.



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-based 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 (CO₂) 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂.

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 CO₂. Animals, especially ruminants such as cattle, sheep, and goats, produce methane (CH₄) during enteric fermentation. Animal waste (namely manure and urine) also goes through a process of decomposition, releasing methane (CH₄) and nitrous oxide (N₂O), 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 N₂O, another potent greenhouse gas. Urea, a nitrogen fertilizer, also emits CO₂ during decomposition. Correctives such as lime generate CO₂ when added to the soil, as does the burning of pastures or crop residues, which generate not only CO₂ 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 (PNCPP) (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

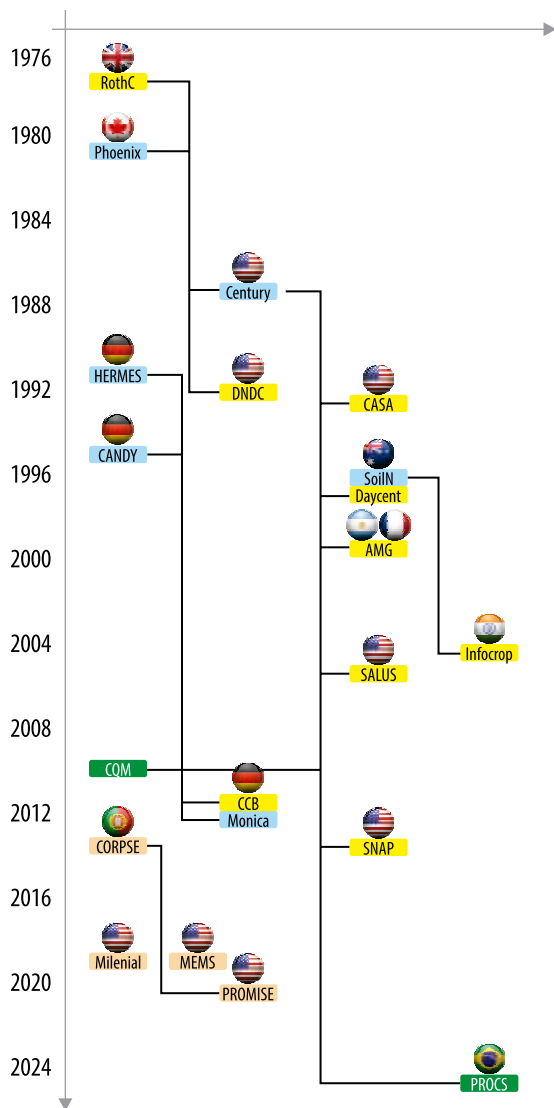


Figure 3.1. History, nationality, and origin of the main soil carbon dynamics models used worldwide.

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 (Vol), 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, Pecu, 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

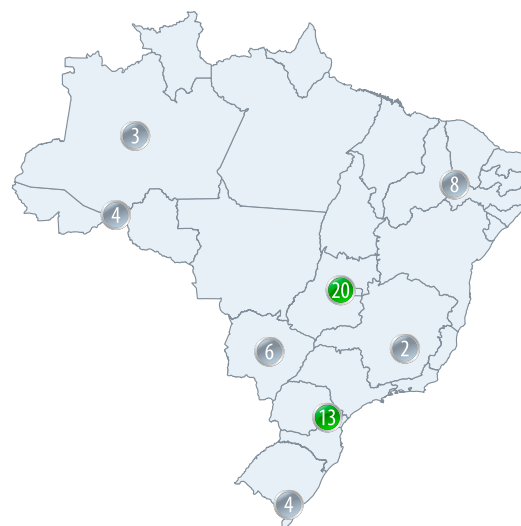


Figure 3.2. Locations of long-term experiments generating information on carbon and other indicators which is stored in REDAPE. The numbers indicate the number of experiments conducted in the region.

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>.

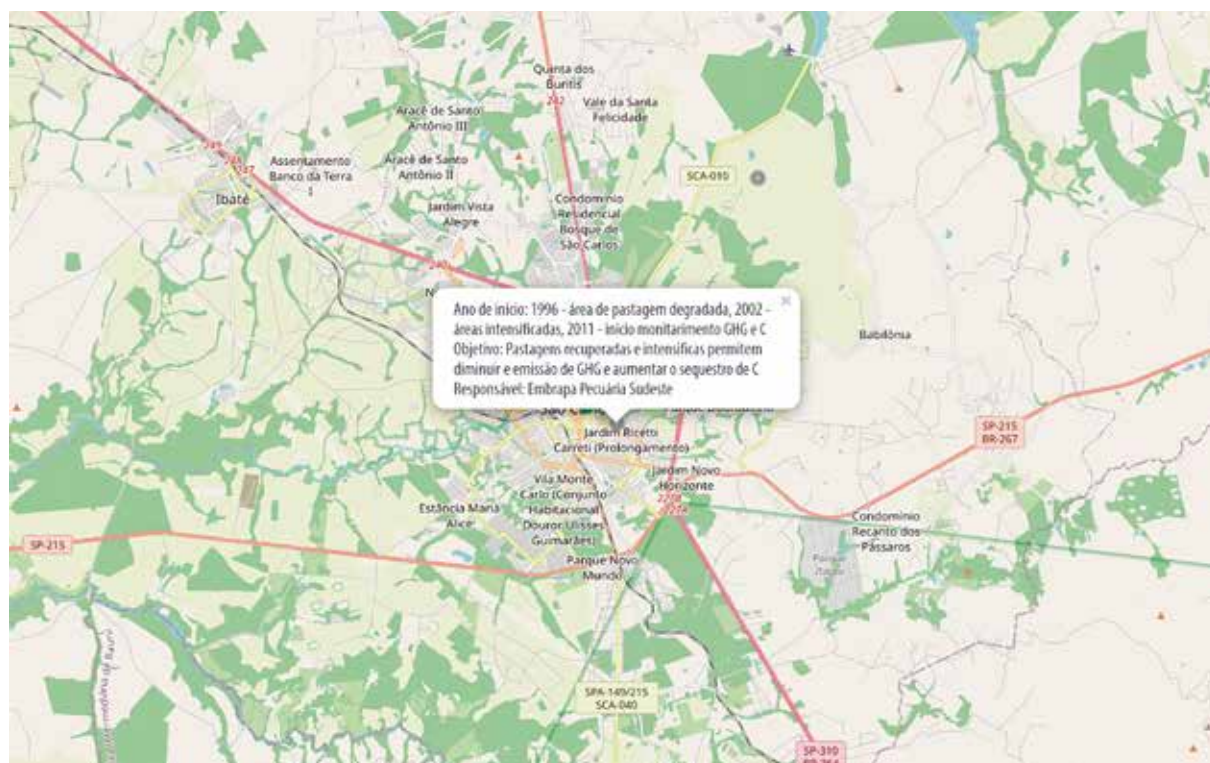


Figure 3.3. Metadata from one of the data collections on carbon available in REDAPE, referring to pastures used in research on carbon in livestock production. Text in the bubble indicates a starting year of 1996 with a degraded pasture, followed by intensified use in 2002 and the start of GHG and C monitoring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

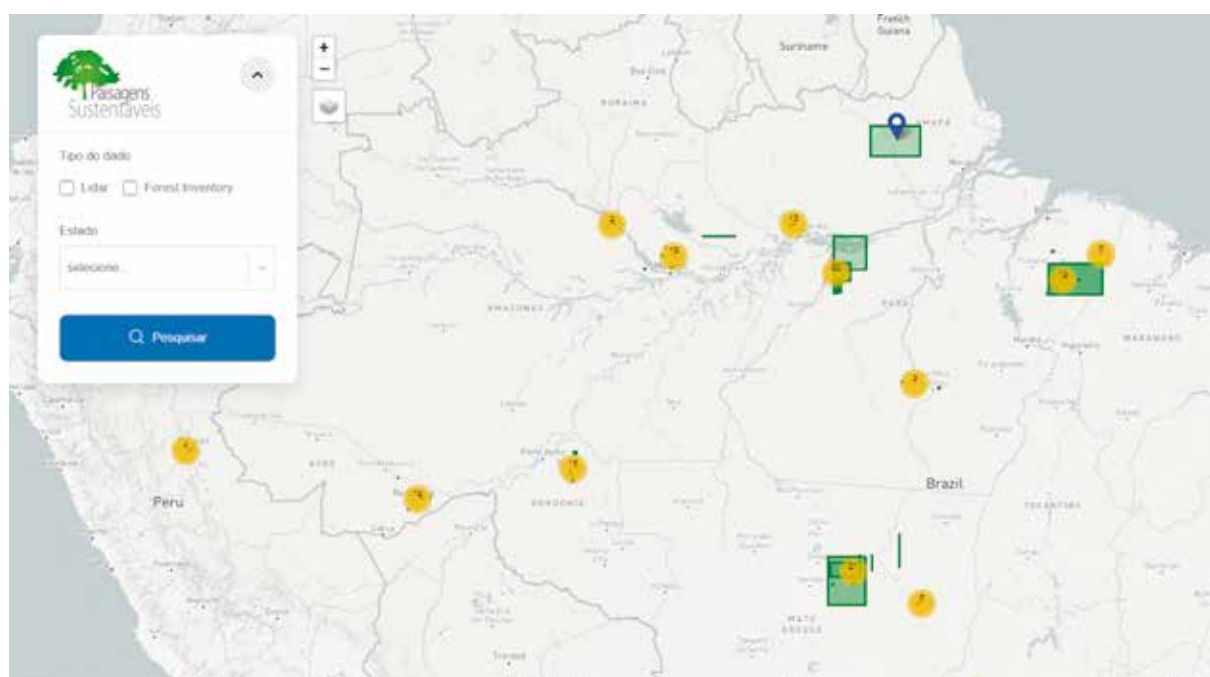


Figure 3.4. Map showing data from forest inventories and LiDAR surveys published in the REDAPE repository.

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.

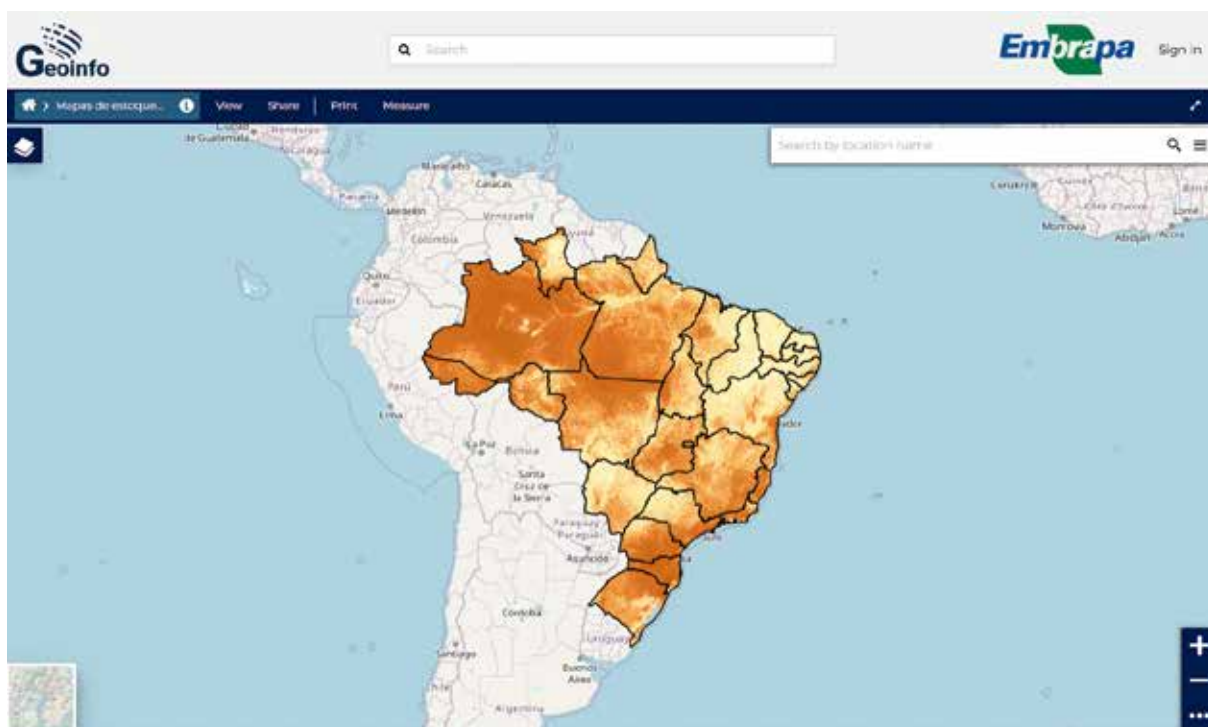


Figure 3.5. Map depicting soil organic carbon stocks in Brazil, at 1 km spatial resolution.

Source: Embrapa (2025a).



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

Source: Embrapa (2025b).

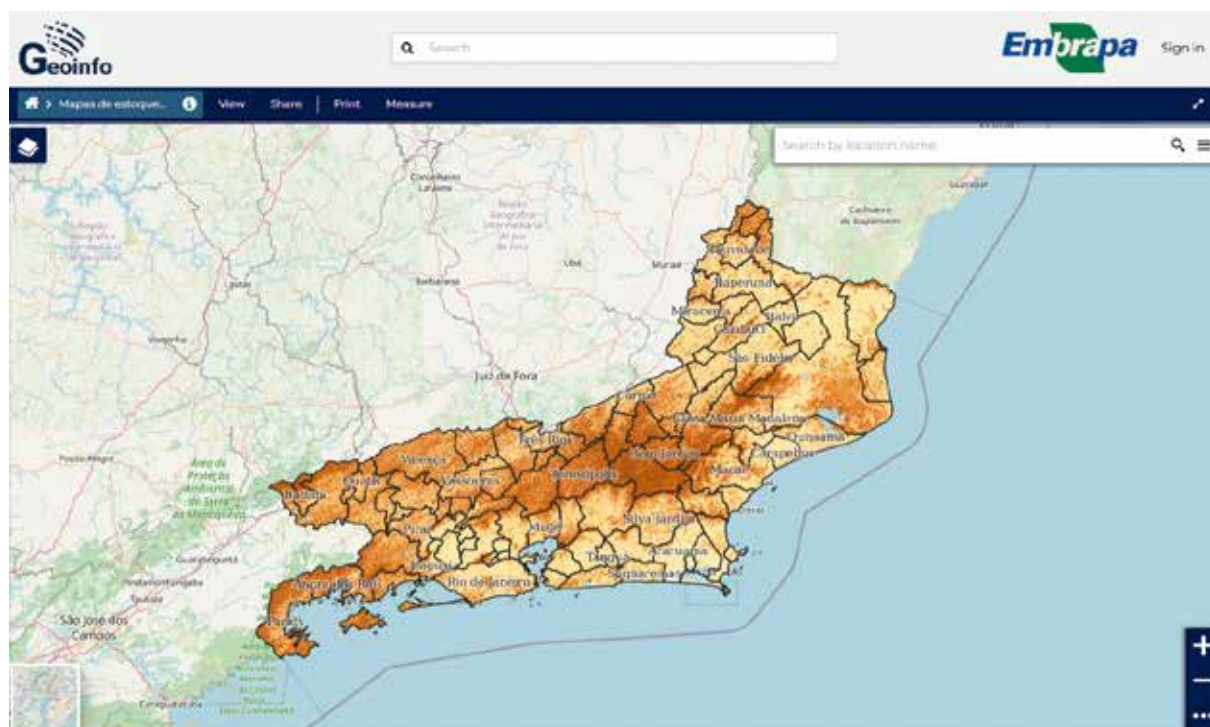


Figure 3.7. Map depicting soil carbon stocks in the state of Rio de Janeiro.

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.

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 Embrapa⁵, INFOTEC-A-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

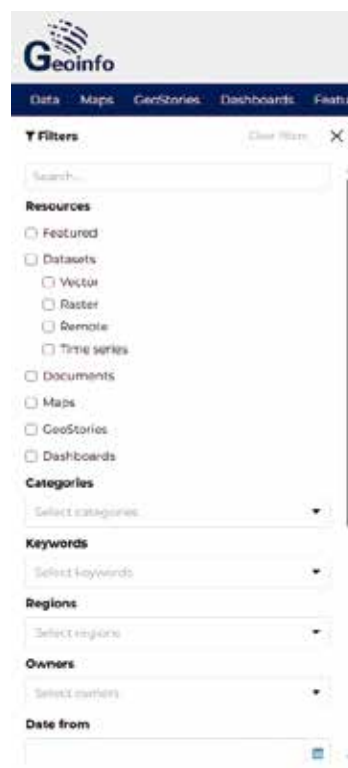


Figure 3.8. Some of the filters available in GEOINFO.

Source: Embrapa (2025e).



Figure 3.9. QR code to access GEOINFO.

Source: Embrapa (2025e).

technical notes, while the INFOTEC-A-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 Nelore, 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: CO ₂ evolved and decomposition rate.	VASCONCELLOS, C. A.
1996	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.
Resultado 1-10 de 497.		

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).

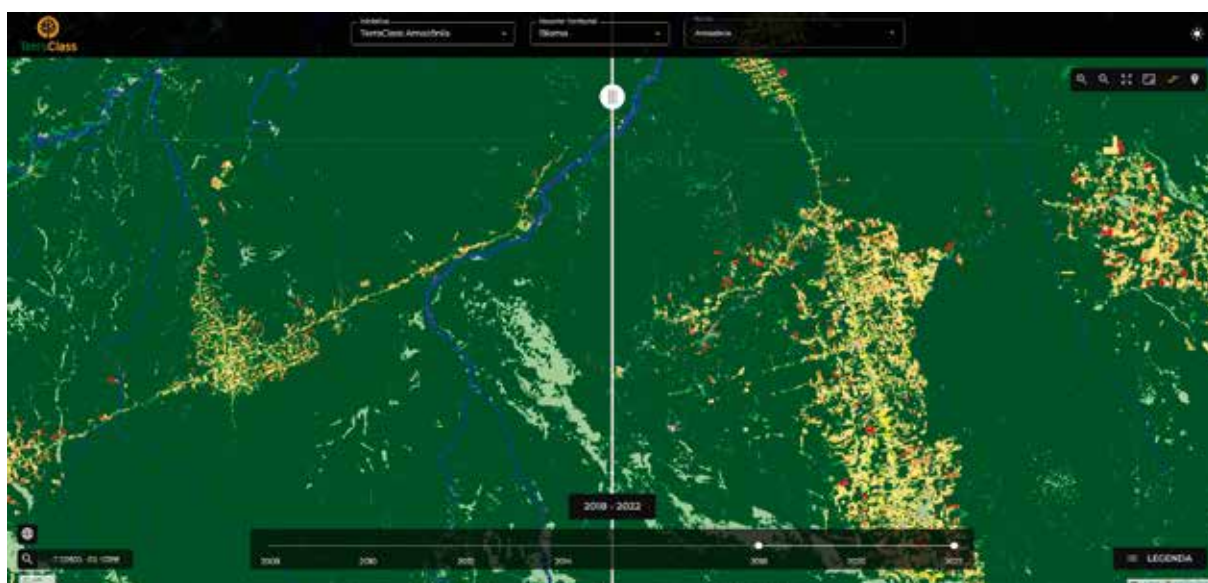


Figure 3.13. Visualization of changes in land use over time in the Amazon biome.

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.

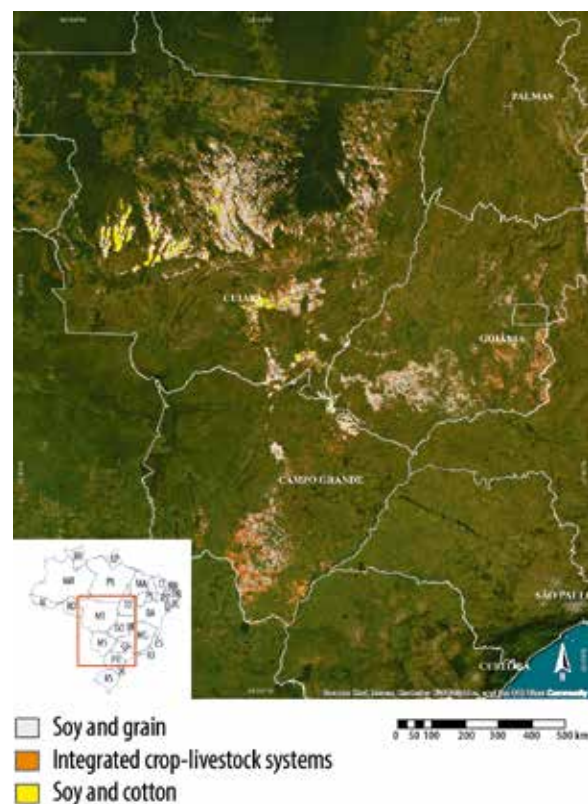


Figure 3.14. Spatial distribution of the different modes in the soybean chain for the states of Mato Grosso, Mato Grosso do Sul, and Goiás in the 2020/2021 harvest year.

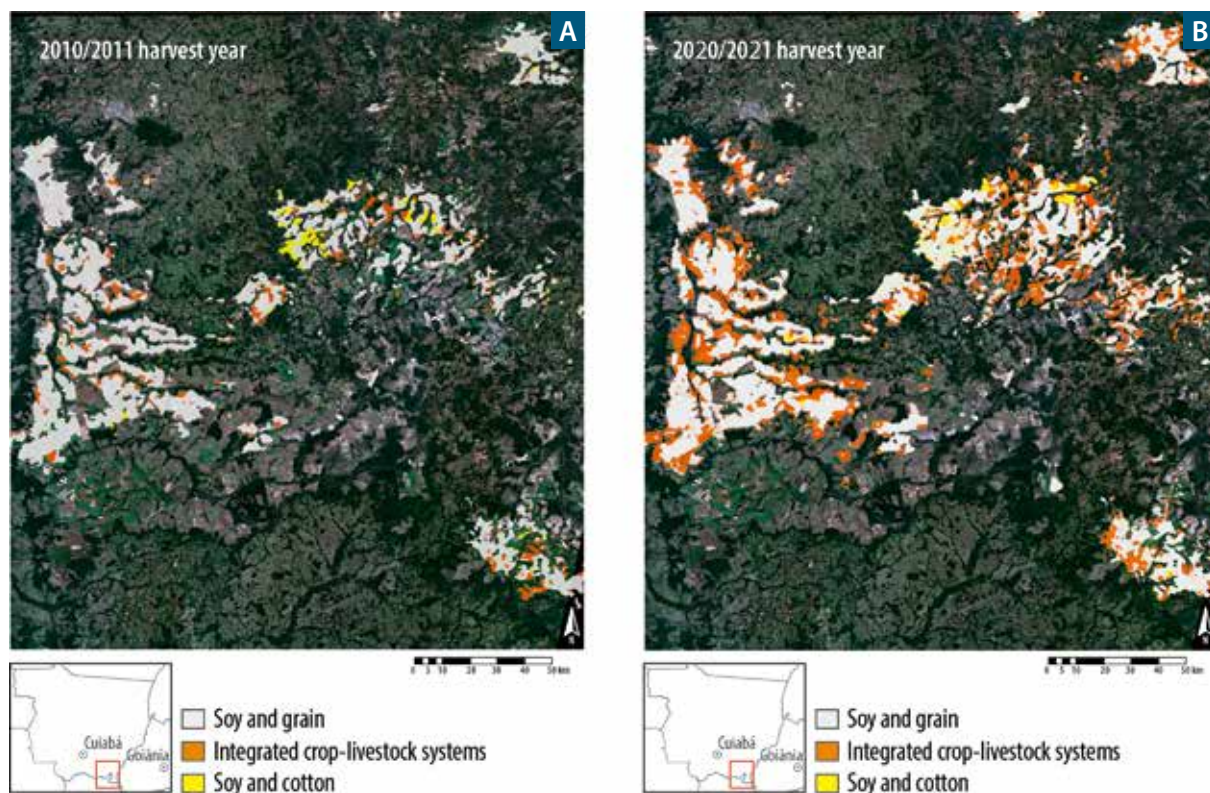


Figure 3.15. Detail (southern region of the state of Mato Grosso) of expansion in soybean modal systems for the 2010/2011(A) and 2020/2021(B) harvest years.

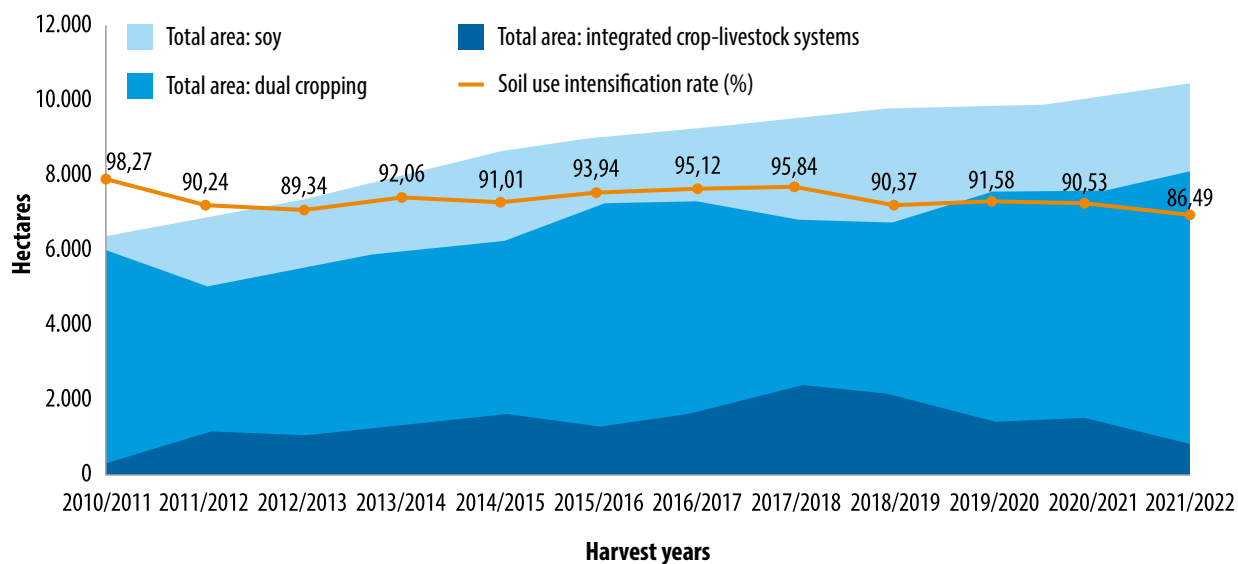


Figure 3.16. Expansion in area (ha) for the different modes in the soybean production chain in the state of Mato Grosso do Sul, 2010–2022.

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 PronaSolos⁶) 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 Portal⁷ 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 MapBiomass 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.

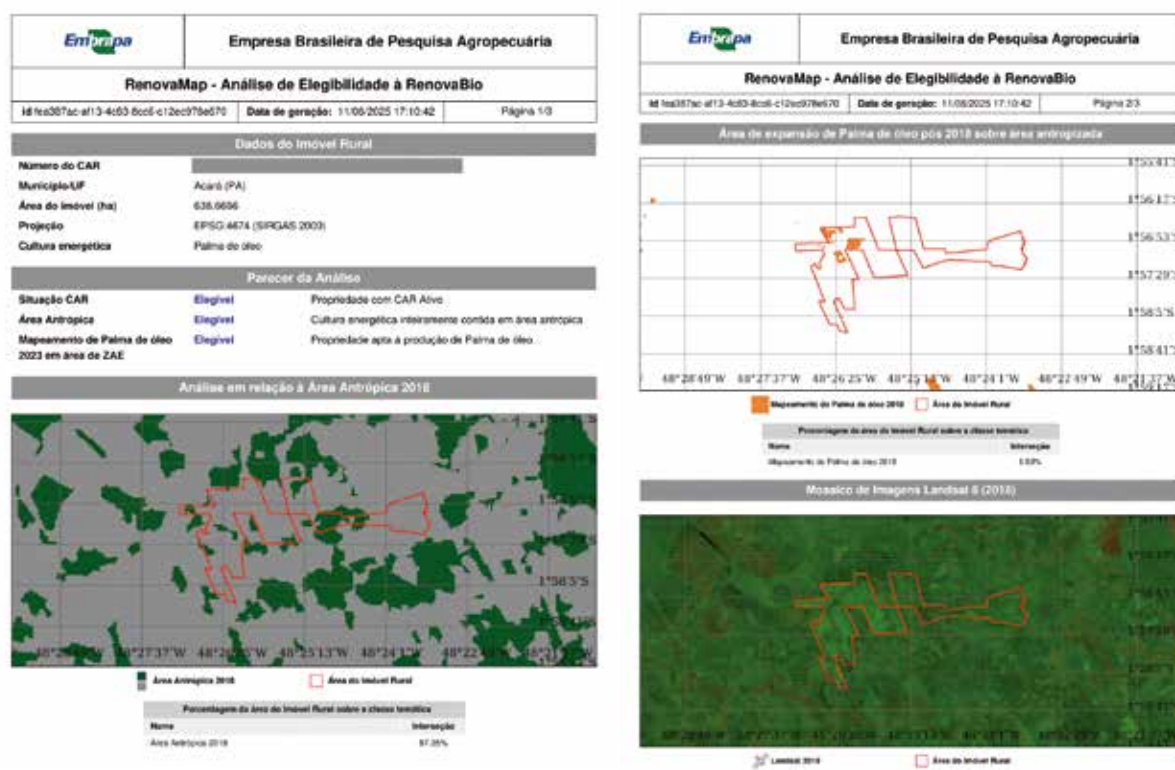


Figure 3.20. Report generated by the Renovamap System.

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 database⁸ 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 solution¹¹ 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.

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From the field to the climate

How **Brazilian milk** is reducing its emissions

In the face of global climate change, reducing greenhouse gas emissions has become one of the greatest challenges of our time. Agriculture, which is essential for food security and economic development, also needs to deal with this urgent matter. Brazil is a country that spans a continent, with landscapes that change radically from north to south and from east to west: mountains, plains, forests, savannas, with a mosaic of cultures, accents, and ways of life. In this diverse context, thousands of families make their living from milk production.

As more attention focuses on the environmental impacts of food production, one question has started to resonate more strongly: what is the carbon footprint of Brazilian milk?

Brazil is not exactly a country of averages or specific values — it is more a country of contrasts and diverse realities. Understanding and accurately quantifying the carbon footprint of milk is an essential step in moving towards more sustainable systems. The journey began with developing life cycle inventories for milk, a fundamental step in identifying emissions sources along the production chain. This effort paved the way for something even broader and more relevant: partnerships with the country's main dairies. Producers, researchers, and companies began to map what happens in each dairy catchment area in Brazil, region by region and system by system.

It was against this backdrop that Embrapa Dairy Cattle began a pioneering partnership with major

companies in the sector, focused on systematic collection of field information and generation of qualified technical knowledge. The result was the construction of the largest and most representative database on the carbon footprint of milk in Brazil, fed by real data collected directly from farms in all regions. This approach makes it possible to capture local variability (in climate, geography, production system, and culture) and offers a realistic portrait of national dairy production.

The database continues to grow and consolidate itself as a reference; more than just a repository of data, it has become a strategic tool, constantly updated by ongoing partnerships. New collections and revisiting old data make it possible to follow the evolution of practices, and identify precisely where there is room for improvement. Continuous monitoring allows planning for the future, based on concrete evidence.

Throughout this process, something powerful happened: data stopped being just statistics or numbers on computer spreadsheets, and started to bring about real change. Producers who were previously unaware of the environmental impact of their activities now see clearly where their bottlenecks, and especially their opportunities, are found. Many have adopted more efficient practices, reduced their waste and emissions, and now feel like they are part of the process and valued, now that they have access to information that speaks to their reality, their system, and their way of producing.

Meanwhile, companies have found the database serves as a compass to guide investments and strategies. And public policymakers now have a solid foundation on which to base decisions that are fairer, more effective, and more sensitive to regional characteristics. Each piece of data represents a possibility for action — and transformation.

Today, this database is a national and international reference. It serves to support public policies, guide research, and clearly show that there is no single carbon footprint for Brazilian milk. There are many footprints, just as there are many stories, practices, and landscapes that comprise this production. This case is an example of how science, data, and collaboration can transform agriculture, adapting it to the contemporary demands of food security, resilience, and sustainability.





CHAPTER 4

Affordable and scalable techniques and tools for field monitoring of carbon and greenhouse gas data

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Introduction

Climate change intensified by greenhouse gas (GHG) emissions is one of the greatest challenges facing humanity this century, mainly due to its effects on food production and water availability. The social, environmental, and economic impacts are likely to become increasingly intense if no significant reduction in GHG emissions is attained. The United Nations Framework Convention on Climate Change (UNFCCC) established a universally agreed regulatory environment for countries to quantify their GHG emissions. Recently, the Paris Agreement made progress in establishing a periodic instrument to expand these ambitions internationally, in order to stabilize the increase in average global temperature at 1.5 °C (preferably) or 2.0 °C.

In this context, during the 26th Conference of the Parties (COP 26) to the UNFCCC in Glasgow, Brazil made a commitment to neutralize its emissions by 2050. This commitment is described in the Nationally Determined Contributions (NDC). Many organizations which are equally committed to this commitment (and possibly pressured by more demanding consumer markets) have also presented their ambitions to reduce GHG emissions over the next 30 or 40 years, in anticipation of the debates and regulatory policies that will need to be implemented to guarantee action from the economic agents responsible for emissions. At the same time, consumer markets will increasingly demand products

and services that are less emissions-intensive (in terms of GHG emissions per unit of product) or more environmentally friendly. For this reason, there is a growing initiative among organizations to determine their contributions in terms of GHG emissions and removals in order to plan a transition towards neutrality or a significant reduction in these emissions.

As institutions search for ways to reduce and offset their GHG emissions with a target of “net zero” (in other words, to bring the impact of their emissions to zero), this has created an increasing demand for information on how to measure the carbon present in the environment, calculate the amount of polluting gases emitted, and set targets for reducing these emissions over time. Clearly defining strategies to monitor and control GHG emissions has become an important aspect in winning over markets, differentiating prices, and enhancing the value of brands and companies, and is now part of environmental and economic agendas at many organizations. The growing proliferation of corporate initiatives, coupled with the regulatory inducement established by the Paris Agreement, has driven the creation of instruments intended to improve climate performance and corporate environmental sustainability, such as voluntary markets, green and climate bonds, and the environmental, social, and governance (ESG) movement. This dynamic new panorama brings with it opportunities and challenges for managers, granting priority to climate management as a strategy for minimizing and offsetting emissions. The entire process, however, requires systematic monitoring, reporting, and verification practices (known by the acronym MRV).

In climate performance projects, the monitoring stage consists of generating information on emissions, removals, and other indicators related to climate change mitigation or adaptation criteria. Data collection for this monitoring can

take place through inventories, estimates based on emission scenarios (using mathematical modeling), or direct measurement of climate-related targets and metrics, on a one-time or periodic basis. The reporting stage consists of transparent and accessible disclosure of this information to stakeholders. The verification stage corresponds to analysis of the disclosed information, ensuring its reliability through traceability audits and replication of the methodology in accordance with its purpose.

Like the other signatories to the Convention and the Paris Agreement, Brazil has committed to periodically inventory its emissions according to the methods and principles recognized for transparency, accuracy, consistency, compatibility, and completeness (TACCC) which have been established by the Intergovernmental Panel on Climate Change (IPCC). This activity must use the internationally agreed methodological framework recognized by the Convention of the Parties. It is up to Brazil, as a signatory to the Paris Agreement, to determine the set of nationally appropriate measures to foster an economic transition towards foundations which involve less intensive GHG emissions, as established in its NDC. The country has already carried out five national inventories (2004, 2010, 2016, 2020 as a National Communication, and 2024 as a Biannual Transparency Report), but still relies heavily on information based on technical coefficients and specific emission factors, since it does not yet have indicators measured on a national scale (Brasil, 2021, 2024a).

With the Paris Agreement in force, Brazil is entering a new phase where it will be required to draw up biannual GHG inventories, as well as demonstrate compliance with the emissions reduction targets determined in its NDC. Lack of information on the mitigation potential of agricultural systems and activities also affects the production sector, which needs to prove

that its corporate climate performance targets have been met. Brazil's GHG emissions are mainly concentrated in the land use change sector (associated with deforestation and fires) and the agricultural sector (Brasil, 2024b). Both generate diffuse emissions which, considering the geographical expanse of the country, represent a major challenge for comprehensive and effective monitoring of emissions and removals.

Data collection is the backbone of any analysis, decision making, and direction-setting strategy. For a country like Brazil that spans a continent, accurately representing all environments and production models with viable costs and a satisfactory timeframe represents an additional challenge. This is why improving monitoring, reporting, and verification techniques has become a priority in Embrapa's work. The aim is to generate and adapt techniques and instruments that make collection and monitoring methods more accessible and scalable, permitting use on a large scale and with frequency appropriate for meeting national commitments as well as the needs of the productive sector. Many techniques and field evaluations can provide important inputs for analyzing GHG mitigation and adapting production systems to climate change.

This chapter highlights the collection and monitoring techniques adapted or developed by Embrapa to obtain technical coefficients for crops, estimate carbon stocks in different ecosystem compartments, measure GHG emissions released by soil and animals in production systems, as well as measure environmental and soil attributes that are essential for estimating emissions and removals, or even for understanding GHG emission and removal patterns. One of the premises adopted is that these techniques should be compared and validated with traditional field data collection methods, which are generally more expensive, require more manpower or specialized skills,

and in many cases are too invasive, since they alter the collection site or destroy the sample. Alternative techniques must have the advantages of accessibility, agility, and lower cost, and also be easy to apply on a large scale.

The state of the art

Throughout its history, Embrapa has effectively contributed to continuous growth in the country's agricultural production and productivity, boosting the competitiveness of Brazilian products in international markets, food security for Brazilian and global society, conservation of natural resources, environmental preservation, and finally to building and consolidating technical and scientific competence and leadership for conservationist tropical agriculture (Hungria; Vargas, 2000). One of the main challenges today (and also over the next 10 to 20 years) is to offer strategies for the ecological transformation of the economy, enabling innovative technologies that guarantee production of food, fiber, and energy within a global scenario of climate change that includes strong pressure on water, soil, biodiversity resources, and growing demands to reduce the environmental and social impacts of the production process.

Embrapa's role on the topic of climate change is very broad, supporting everything from the definition of climate mitigation and adaptation strategies to domestic estimates of GHG emissions and removals, since the first edition of the national inventory. Its work includes improving technical coefficients for crops, estimating sequestration rates and carbon stocks as a result of changes in land use and management practices, as well as defining emission factors adapted to national conditions (Brasil, 2020).

In recent years, Embrapa has increasingly been called upon by the private sector to help with emissions accounting, mainly in carbon balance and footprint calculations, estimates of GHG emissions, and characterization of environmental profiles for products. The carbon balance, like other related metrics, has become an important aspect in measuring the achievement of corporate targets to reduce GHG emissions. This measurement is essential for winning markets, differentiating prices, and adding value to brands, and is currently part of many organizations' environmental and economic agendas.

Given the growing number of corporate initiatives, associated with the regulatory inducement established by the Paris Agreement, there is also a growing need to improve techniques for collecting and monitoring GHG emissions in the agricultural and land use change sectors. The collection and monitoring of field data can be carried out using different technologies; the most suitable technique depends on the scale and the variable to be monitored. Within this context, Embrapa has been developing and adapting techniques and instrumentation to reduce costs, increase scalability, and speed up collection of data related to GHG flows, the carbon present in various compartments including the soil, and other equally important environmental aspects.

By increasing the efficiency and accuracy of the data generated, investments in expansion of collection infrastructure and methodological standardization of alternatives to traditional methods will have a strong impact on monitoring viability. These advances are relevant for the national GHG inventory, as well as for certifications, incentive programs, and commitments made by smaller-scale enterprises to achieve climate performance targets.

The agricultural sector is of great economic importance to Brazil, and occupies 32% of the country's territory. However, most of the

country's area is covered by native forests, which account for 59% of the total and are in different states of preservation (Table 4.1). There are an additional 10 million hectares of planted forests, which correspond to 1% of the national territory. Brazil's native forests have high biodiversity and varied plant formations, which makes it difficult to measure carbon and GHG emissions in a representative manner. Despite these challenges, they are essential for meeting the targets set in the Paris Agreement, and in the national NDC they stand out as the most important sector for mitigating GHG emissions.

Table 4.1. Area allocated to individual land uses in Brazil, with agriculture broken down into the main sectors, based on MapBiomass data (2024).

Land use	Area (ha)	Area (%)
Forest	502,572,052	59.0
Shrubby and herbaceous vegetation	46,450,811	5.5
Area without vegetation	6,773,077	0.8
Bodies of water	18,298,211	2.2
Agriculture and livestock production	276,671,946	32.5
Pasture	164,574,066	59.5
Agriculture	60,992,647	22.1
Forestry	8,940,366	3.2
Other uses	42,164,867	15.2

The traditional method for estimating carbon stocks in forest biomass is based on field inventories. These surveys collect information such as tree diameter and height and identify species and botanical families. This data makes it possible to assess the quantity and quality of forest resources as well as to monitor tree mortality and growth over time, providing a more accurate view of the dynamics of the area studied. The stored carbon is estimated using

allometric equations, which relate tree size to biomass. These equations can be specific to a plant species, or generic, applied to groups which do not have their own specific models.

The sampling method is most widely used, with part of the area assessed and considered representative of the whole. Field inventories are essential for estimating carbon stocks in plant biomass, but they present significant challenges: they require trained teams, take a long time, and are labor intensive. Moreover, subsequent processing of the data can be as time-consuming as the field collection itself, which may complicate revisions in the event of errors or questions. Due to their laborious nature, field inventories are of limited efficiency in generating data on a large scale, especially given the commitments made on a national scale.

Indirect methods based on non-destructive technologies have shown promise for expanding the capacity to generate information and supplement national inventories. New devices and methods are emerging every day with the evolution of geotechnologies, which has greatly benefited planning and execution of forest inventories and placed this activity in a new light. In this way, field inventories have gained new tools like remote sensing, through various techniques such as satellite images, unmanned aerial vehicles (UAVs or drones), and LiDAR scanning (Sousa et al., 2020; Santos et al., 2021; Ferreira et al., 2022; Costa et al., 2023). But like any new tool that arrives in the field, they need to be adjusted to the conditions and subjects where they will be applied, in turn requiring new models and response algorithms that are consistent with each forest situation (Souza et al., 2024).

In this context, Embrapa is developing techniques to identify forest species, quantify forest attributes, and estimate the carbon stocks present in plant biomass. These techniques vary widely in cost; services involving drones or UAV

are most affordable, which makes it easier for the public to access these technologies. However, data processing still requires qualified human resources to ensure credible results.

The carbon present in the soil is just as important as that stored in vegetation. Agriculture and land use greatly influence the amount of carbon stored in the soil, which can be equal to or even greater than the quantity found in vegetation. In 2021, Embrapa released a map depicting soil carbon at 90 m spatial resolution (the equivalent of 1:250,000–1:100,000) in sub-layers up to 100 cm deep (Vasques et al., 2021). Although it represents a strategic advance, this database cannot yet be used as a reference for rural properties or to monitor changes in carbon stocks caused by good agricultural practices like no-till farming, integrated crop-livestock-forest systems, and the use of bioinputs.

Two main measurements are required to monitor soil carbon stocks: carbon concentration and soil density. Both are costly assessments, in terms of both physical effort and financial cost. On the other hand, soil carbon monitoring is gaining importance, and the search is intensifying for faster and more accessible methods for collecting and analyzing soil samples. These methods must be efficient, affordable, and generate as little laboratory waste as possible.

Accurately quantifying the temporal variation in carbon concentration is a challenge, given its slow evolution over time and high variability in space (Haynes, 2005). In order to monitor and analyze soil carbon variation, it is essential to define reliable quantification methods. Carbon can be measured using dry combustion methods (ISO 10694:1995) as well as wet processes, such as the Walkley-Black method (FAO, 2020), which oxidizes the carbon present in the sample with a potassium dichromate solution and is also known as wet combustion. While this method has the disadvantage of generating a large amount of chemical waste, it is the

most common process used in soil analysis laboratories that serve rural properties in Brazil, since it is relatively inexpensive and does not require the use of specialized equipment.

Although the data obtained with this method are widely used to calibrate nitrogen fertilization recommendations for many crops, their application in monitoring changes in soil carbon stocks has been questioned. This is due to the inherent inaccuracy of the results, since oxidation of the carbon in the most transformed fractions is not complete and depends on the recalcitrance (physical-chemical stability) of the carbon present in the sample (Fontana; Campos, 2017).

The dry combustion method is considered the international standard, and is widely accepted and recognized due to the high precision and accuracy of results (Nelson; Sommers, 1996; Fontana; Bianchi, 2017). In this method, the soil sample is incinerated at a temperature of at least 925 °C, which results in complete oxidation of all forms of carbon present, transforming them into CO₂. The C-CO₂ is then detected using an infrared sensor. The main disadvantage of this method is the high cost of analysis, which exceeds that of the wet method. This cost stems from the need for specialized equipment, consumption of specific materials, and high maintenance costs, making it accessible only to a few commercial laboratories with high demand for analysis and limiting its application on a large scale.

In response, Embrapa and its partners have sought to develop technical methods that are robust, accessible, and capable of meeting national demands on an adequate scale. Two technologies derived from these initiatives that are currently available in the private sector are AgLIBS (Babos et al., 2024a) and the use of Vis-NIRS (Coelho et al., 2018). Both stand out for their low cost and agility of analysis, as well as the fact that they are already accepted in voluntary market certification programs. The use of technologies such as radio detection and

ranging (RADAR)/synthetic aperture radar (SAR) also shows promise for monitoring and assessing carbon in soil and roots (Machado et al., 2025), and is already being investigated in research projects.

Soil density (Ds, also known as bulk density) is a fundamental factor in calculating carbon stocks, and represents the greatest source of uncertainty in this process. As interest grows in determining changes in soil carbon stocks because of their role in reducing GHG emissions, assessment of Ds has become indispensable and is now required on a broader scale. The methods available for determining Ds are laborious and require specific caution as well as the use of appropriate tools, which limits their application in large areas or studies with many repetitions because of the meticulous work and the high operational costs involved.

Ds can be determined directly, by taking undeformed samples of a known volume of soil in the field, or indirectly by estimating it via mathematical equations. Standard methods include the volumetric ring and excavation, both of which are recognized by national (Oliveira, 2014; Zanatta et al., 2015; Fontana et al., 2024) and international (FAO, 2020) protocols. These methods require a trench to be dug either manually or mechanically, usually 50 to 100 cm deep, to access the layers of interest.

In the volumetric ring method, a cylinder of known volume (ring) is carefully inserted into the soil in order to preserve its structure. The soil contained in the ring is then removed, dried and weighed. Soil density is calculated as the ratio between the dry mass of the soil and the volume of the ring. The excavation method is suitable for loose soils or soils with a high gravel content, when more than 15% of the volume is made up of coarse materials. In this case, a “hole” is made in each layer of soil, which is filled with fine sand of known density (density of sand = mass of sand / volume of sand). The Ds of the soil is calculated

based on the ratio between the mass of dry soil extracted and the volume occupied by the sand used.

The trenches opened to apply these methods must be properly closed after collection, which takes time and a great deal of effort, whether manual or mechanical. To avoid this step, automated methods have been proposed that use probes to obtain undeformed samples. However, these techniques still need to be validated against reference methods such as the volumetric ring. Collection via automated probe obtains a soil monolith (or core) that can be subdivided into layers of interest, after which Ds can be determined according to traditional procedures.

The most modern methods for determining Ds are based on nuclear techniques, such as computerized tomography (Timm et al., 2005; Pires et al., 2010) and the use of neutron-gamma surface probes (Cássaro et al., 2000a, 2020b, 2020e). Both techniques use very expensive equipment and require highly skilled labor, which means they are very costly to implement.

Alternatively, technical teams have developed Ds prediction models that use some attributes obtained from disturbed samples after routine soil analysis, such as particle-size fractions (sand, silt, and clay), C, pH, and sum of bases, which are correlated with soil aggregation and structure. The models known as pedotransfer equations are well accepted, and may offer alternatives with interesting cost-benefit ratios. Some models that are already available are described under innovative solutions for soil density, along with technical adaptations for the use of automated mechanical probes. These solutions serve the productive sector, since they are inexpensive techniques that can be applied on a large scale and with adequate operational performance. This approach will be detailed in the technological solutions section, since teams are developing

prediction models with very satisfactory results (Reis et al., 2024; Santos et al., 2025).

Monitoring GHG flows is also a very laborious activity. Methodologies for assessing GHG flows *in situ* in the soil-atmosphere system generally require the use of chambers to collect samples and then analyze them in the laboratory. Manual static chambers are most commonly used to measure soil gas flows, because they are portable, simple to operate and can be inexpensive, depending on the method used (Dalal et al., 2003; Parkin; Venterea, 2010). When used according to recommended criteria, these chambers are very valuable and cost-effective (Hutchinson; Rochette, 2003; Parkin; Venterea, 2010).

Despite being widely used around the world, chambers present significant operational challenges. The method requires a great deal of work, and has limitations related to sensitivity, frequency of evaluations, and the need for specialized labor to interact with the system and collect the air samples. Furthermore, efficient collection depends on both the capacity of the collector and the distance between the chambers, restricting application on a large scale. One person can normally collect samples from up to 10 chambers, distributed over a radius of up to 30 m. This capacity limits the number of repetitions and replicates to be monitored, making comparative analyses difficult due to the low number of field repetitions. It is important to note that soil GHG flows are influenced by several factors (La Scala et al., 2000; Jantalia et al., 2008; Veloso et al., 2019), resulting in high spatial and temporal variability (Deng et al., 2020). It is consequently necessary to increase the number of repetitions in the collection to obtain more accurate and representative results.

Another limiting condition is that in systems with manual collection, it is practically impossible to carry out daily monitoring of GHG emissions over consecutive days. These difficulties severely

limit studies that are more comprehensive in terms of time and space. Flow towers provide indirect measurements of GHG flows on a highly detailed and representative time scale for a larger area, typically between 2 ha and 10 km²; this size depends on the characteristics of the monitored area as well as installation of the towers, making them valuable tools for large-scale studies. However, the results obtained by this method are not directly comparable with those obtained from chambers installed in the ground, because while flow towers describe the GHG balance in the soil-plant-atmosphere system, the chambers represent the net flow in the soil-atmosphere system. Because of the inherent characteristics of the tower method, installation requires large areas of relatively flat terrain, as well as qualified professionals for operation and maintenance.

One way to expand collection capacity when using chambers is through automatic systems for collecting air and analyzing the flow of GHGs. These systems are connected to a gas analyzer, which may be a gas chromatograph or laser spectrometer. In this case, the chambers are programmed in advance and air samples can be taken and analyzed several times a day. Despite the excellent quality of the information generated, use of these systems is restricted to experimental fields with adequate security and depends on the presence of analysis equipment in the field, which for chromatographic systems implies limitations in terms of equipment sensitivity, since it operates under controlled temperature conditions. This technique yields very large amounts of data, and can lead to much more accurate conclusions about daily emissions cycles and also identify the direct response of the GHG flow to changes in soil conditions, especially temperature and humidity. All of the automatic chambers currently available on the market are imported and still relatively expensive, and must be adapted for use in Brazilian conditions.

Considering this challenge, Embrapa and its partners developed a semi-automatic sample collection system that the operator can bring into the field, turn on, and return at the end of the campaign (usually 2 hours) to collect the air samples and the device. This new system boosts collection capacity in the field involving one operator at least three-fold compared to the traditional collection system (involving a manually operated static chamber).

Many of the difficulties mentioned for monitoring soil GHG fluxes are also true for monitoring enteric methane from ruminant animals. Monitoring enteric methane requires non-invasive methods that are sufficiently accurate, which represents an additional difficulty. Rumen fermentation is a complex process influenced by various factors such as type of diet, forage quality, animal genetics, and environmental conditions. Generalizing the results to different production systems requires studies with large numbers of animals and multiple conditions. Methods for measuring enteric methane include containment chambers, tracer techniques, sniffing techniques, and portable laser methane detectors. While methods like breathing chambers are accurate, they are invasive and limited to a small number of animals. The search for portable and less intrusive methods, such as laser methane detectors, is underway. More recently, an automated head chamber system known as GreenFeed (GF) has been developed for spot sampling of exhaled and eructated gases (Zimmerman; Zimmerman, 2012). Comparisons with respiration chambers or the SF₆ method have established that, when used correctly, GF is a reliable technique for measuring enteric methane emissions from ruminant animals (Dorich et al., 2015; Hammond et al., 2015).

Many techniques and tools have been developed to facilitate monitoring and increase access to field data. The evolution of these techniques is also driven by growing demand

from organizations to generate more detailed information on emissions and removals, both to improve climate management and with a view to investing in mitigation mechanisms. Indeed, given Brazil's expansive size, large-scale techniques are essential to provide the country with information that meets the demands of the Paris Agreement rules, as well as to promote efficient planning and control of emissions at the rural property level.

Innovative solutions for monitoring soil carbon

Obtaining accurate, large-scale data on soil organic carbon (SOC) is fundamental for understanding soil health, the global carbon cycle, and the potential for carbon sequestration in agricultural systems (Minhoni et al., 2021; Lima et al., 2025; Petropoulos et al., 2025). The importance of this data lies in the ability to map the distribution of soil carbon over large areas, identify areas with the greatest potential for carbon sequestration or risk of carbon loss, and monitor changes over time in response to management practices or extreme weather events (Minhoni et al., 2021). This information is crucial for implementation of low-carbon agricultural practices and development of climate change adaptation and mitigation policies in the agricultural sector (Petropoulos et al., 2025).

The innovative soil analysis techniques developed by Embrapa, such as AgLIBS and SpecSolo, can make a decisive contribution to strengthening Brazil's role in leading actions aimed at agricultural sustainability and tackling climate change, in direct alignment with the Sustainable Development Goals (SDGs) of the UN's 2030 Agenda, especially SDG 2 (Zero hunger and sustainable agriculture), SDG 12 (Responsible consumption and production), SDG 13 (Action

against global climate change) and SDG 15 (Life on land). These connections reinforce the strategic role of spectroscopic techniques as technologies that enable public policies aimed at the ecological transformation of agriculture and effective monitoring of the environmental commitments made by Brazil at national and international level.

Furthermore, potential techniques are being improved in scientific circles, especially those involving high performance capacity and remote application. From this perspective, data from satellites equipped with SAR sensors like Sentinel-1 and ALOS PALSAR is used through two main techniques: 1) dual polarization, which can be used to estimate SOC (El-Jamaoui et al., 2025) by means of the SAR Vegetation Index (SARVI); 2) ground penetrating radar (GPR), which complements the information obtained by orbital RADAR/SAR, although it operates on a smaller spatial scale, offering details on the structure of the subsoil including root distribution and soil stratification which can influence carbon storage (Jol, 2009). Both technologies will be discussed in the section that addresses future prospects.

The AgLIBS AI platform

AgLIBS AI is a digital platform for quantifying carbon, nutrients, and other physical and chemical parameters in soils. The physical foundation of this platform is laser-induced breakdown spectroscopy (LIBS), a technique which is widely applied in the analysis of materials as well as rocks and soils by various research institutions (Bublitz et al., 2001; Cremers; Radziemski, 2013) that include the US National Aeronautics and Space Administration (NASA) in its last two expeditions to Mars. This is a multi-elemental analysis method, based on atomic and ionic emissions of chemical elements from plasma created by a high-power laser. Figure 4.1 illustrates this technique, showing a

typical emission spectrum indicating one of the emission lines of the carbon atom at 193 nm and a diagram of a typical LIBS measurement system.

The technique has been studied at Embrapa since 2006 as an alternative to traditional methods of analyzing carbon concentration. This technology makes it possible to quantify carbon, soil nutrients, texture, pH, and cation exchange capacity (CEC) more quickly and affordably than conventional methods, and also provides digitized data for analysis and decision making.

As part of a public-private partnership, this technique has evolved into a platform, AgLIBS AI, which generates agronomic recommendations for producers, optimizing soil management. It

also makes it possible to create detailed maps of carbon stocks more quickly and at a lower cost than the dry combustion method, helping to make carbon credit projects viable for rural producers and agribusinesses. Additionally, it permits analysis and mapping of plant macro- and micronutrients present in soils, as demanded by precision agriculture for more efficient and sustainable soil management, resulting in increased agricultural productivity and/or reduced production costs. Importantly, the AgLIBS AI platform is a product with a patent shared between Embrapa Instrumentation and the Agrorobótica company.

In 2023, the LIBS technique was approved by the US-based Verra international certification

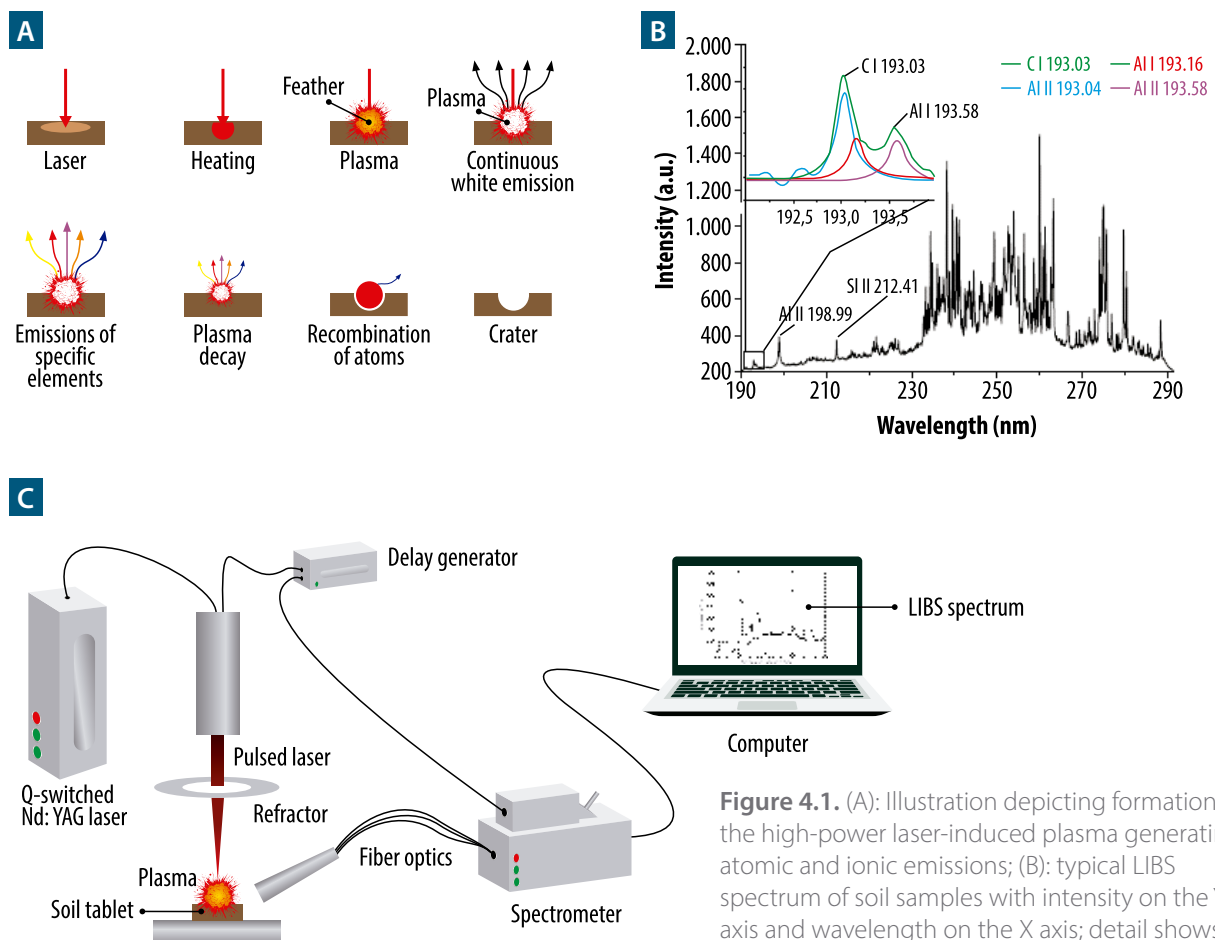


Figure 4.1. (A): Illustration depicting formation of the high-power laser-induced plasma generating atomic and ionic emissions; (B): typical LIBS spectrum of soil samples with intensity on the Y axis and wavelength on the X axis; detail shows detection of the C atom emission line at 193.03 nm; (C): diagram illustrating a typical LIBS system.

program for use in quantifying carbon in the soil, within the Verified Carbon Standard (VCS) program (Methodology VM 0042, Version 2, from May 30, 2023). Among the mostly international publications used by Verra to accept the LIBS technique for quantifying soil carbon in its VM 0042 Methodology, five were published by researchers from Embrapa Instrumentation associated with the Brazilian National Laboratory of Agri-Photonics (Milori et al., 2011; Nicolodelli et al., 2014; Segnini et al., 2014; Villas-Boas et al., 2020a, 2020b).

The AgLIBS AI platform has been used in projects throughout Brazil (Figure 4.2). In some recent results, Babos et al. (2024a) found an average root mean square error of prediction (RMSEP) of 0.47% for LIBS measurements of C; this result was obtained by comparing measurements from over 1,000 soil samples on 11 rural properties. These properties were distributed in the Cerrado, Atlantic Forest and Pampa biomes, with soil

carbon content varying from 0.23% to 8.78%, as determined by the CHN Elemental Analyzer. The coefficients of determination (R^2) between the measurements obtained by LIBS and the CHN Elemental Analyzer were 0.94 and 0.75 for calibration and validation, respectively.

The implementation of advanced technologies like the AgLIBS AI platform has contributed significantly to national competitiveness in the agricultural sector. Adopting technologies like AgLIBS AI not only improves the efficiency and sustainability of agricultural operations, but also strengthens Brazil's position in the global market, meeting demands for more sustainable products and contributing to climate change mitigation. Access to advanced digital tools also allows for more efficient management of rural properties, particularly the ability to monitor and quantify increases in soil organic matter (SOM) and, in turn, soil carbon, with a significant impact on improving soil structure and actions related to adapting to the impacts of climate change.

Although the benefits of proper soil management are widely recognized, resilient and adaptive agriculture will require efficient monitoring of the soil-plant-atmosphere system, linking management practices to changes in SOM. LIBS can also be an important ally in consolidating and benefiting from the adoption of precision agriculture, since it reduces the costs of soil and plant analysis and simplifies application techniques to expand the use of variable-rate management of inputs and pesticides in soils and crops on a large scale.

In addition, the ability to quantify and monitor soil carbon on a large scale creates opportunities for producers to participate in carbon credit projects, generating additional income and granting them access to new international markets that value sustainable agricultural practices. These initiatives are aligned with government programs such as the Sectoral Plan for Adaptation to Climate Change and Low



Figure 4.2. Soil carbon measurement sites using the LIBS technique by Embrapa Instrumentation, from long-term field experiments at public institutions and mainly private rural properties (“on-farm research”), in different production centers and Brazilian biomes. Legend shows Brazilian biomes, while carbon measurements are depicted as green circles.

Carbon Emissions in Agriculture and Livestock, with a view to Sustainable Development 2020-2030 (the ABC+ Plan). Furthermore, the AgLIBS AI platform plays a strategic role in reducing risks and boosting the adaptive capacity of Brazilian agriculture, making farms more resilient and sustainable. By leading investments in sustainability, Brazil not only improves its domestic agricultural practices, but also offers solutions that can be adapted globally, contributing to the sustainability of food production on a global scale.

The SpecSolo platform

The SpecSolo digital platform represents one of the most significant innovations in soil analysis over the past five decades in Brazil, based on the use of infrared spectroscopy. This approach makes it possible to quickly, accurately, and reliably replace traditional methods of analysis, many of which are costly and potentially polluting to the environment.

By eliminating the need for chemical reagents and drastically reducing waste, SpecSolo helps mitigate environmental impacts and reduce laboratory operating costs related to the treatment and proper disposal of this waste. Moreover, the platform has enormous potential for large-scale soil carbon analysis, making it a strategic tool for advancing low-carbon agriculture and the carbon trading mechanism that is currently gaining strength in Brazil.

The SpecSolo platform is based on infrared spectroscopy techniques, which involve the relationship between electromagnetic radiation and matter and are widely used in the physical and chemical characterization of soils. It is essentially based on the selective absorption of energy by specific chemical bonds, promoting vibrational transitions which reflect the molecular composition of the material being analyzed. This capability makes infrared spectroscopy a strategic tool for quantifying soil organic carbon,

permitting identification and estimation of compounds related to organic matter while also providing important information for understanding carbon dynamics and assessing soil quality and fertility.

The spectral regions of greatest agronomic interest include the mid-infrared (MIR, 4,000–400 cm^{-1}), near-infrared (NIR, 1,500–4,000 cm^{-1}), and combined visible-near-infrared spectrum (Vis-NIR, 25,000–4,000 cm^{-1}). Each of these ranges offers specific advantages and can be used in a complementary way, depending on the purpose of the analysis, laboratory logistics, and degree of robustness required for the predictive models.

NIR has established itself as an important alternative for application in large-scale soil analysis due to its speed, non-destructiveness, low cost per analysis, absence of chemical reagents, and possibility of automation. The spectral bands in this region are the result of overtones and ranges that combine fundamental vibrations and result in broad, overlapping bands. For this reason, chemometrics and machine learning techniques are essential to properly interpret these spectra, and include partial least squares (PLS) regression, support vector machines (SVM), random forests (RF), and neural networks (NN), methods which extract information from spectral data and permit simultaneous quantification of multiple soil attributes from a single spectral reading. Figure 4.3 illustrates a typical NIR spectroscopy system, consisting of a monochromator and an integrating sphere, used to collect diffuse reflectance spectra from soil samples prepared as fine air-dried soil.

The Vis-NIR technique further expands this potential by integrating the visible spectrum (400–700 nm), associated with soil coloration and indicative of the presence of organic matter, iron oxides, and mineralogical characteristics. This approach has demonstrated strong performance in predicting physical and chemical properties in tropical soils, such as those found in Brazil.

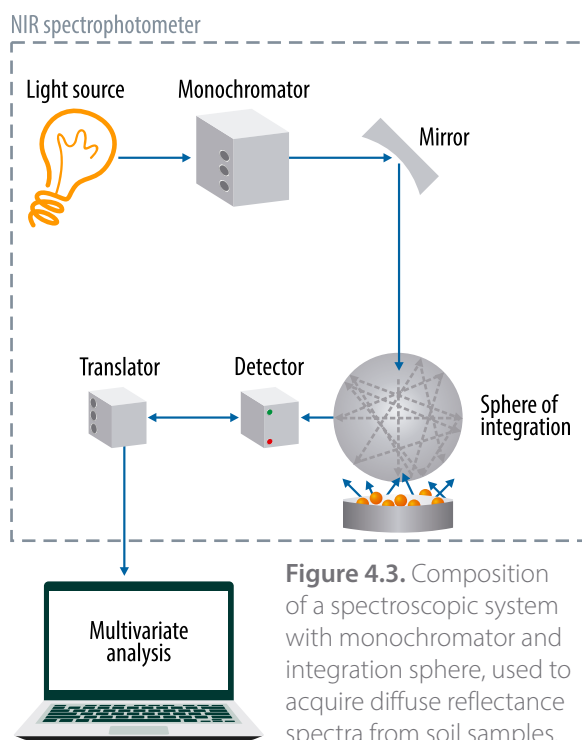


Figure 4.3. Composition of a spectroscopic system with monochromator and integration sphere, used to acquire diffuse reflectance spectra from soil samples.

This is the basis of technologies such as SpecSolo,¹ which uses Vis-NIR spectroscopy integrated with a system of hardware, software, and algorithms hosted in the cloud to offer fast and reliable results for large-scale soil fertility analysis.

This technology is helping to improve Brazil's competitiveness in the face of the challenges posed by climate change. The combination of NIR spectroscopy with artificial intelligence algorithms, along with the consolidation of robust spectral databases and advancement of miniaturized devices, has significantly expanded the potential use of this technique in large-scale routine analysis. Applications of infrared spectroscopy have also been catalyzed by national structuring projects such as those involving soil mapping and monitoring (like PronaSolos) and proficiency testing such as the Programa de Análise de Qualidade de

Laboratórios de Fertilidade (Quality Analysis Program for Fertility Laboratories),² which since 2024 has included carbon measurement using NIR in its proficiency tests. This movement coordinated by Embrapa is intended to ensure methodological standardization, quality control, and inter-laboratory validation of the use of this technique in routine analyses.

By permitting rapid and non-destructive soil analysis, NIR spectroscopy could be integrated into public policy tools (such as Agricultural Climate Risk Zoning, or ZARC) to provide more accurate data on soil carbon content and encourage safer and more sustainable decisions regarding the use and management of agricultural land. Its application is also highly strategic for monitoring and verifying the sustainable practices envisaged in the ABC+ Plan, making it possible to monitor the potential for CO₂ mitigation through soil organic matter (SOM) content and carbon stocks, key indicators for low-carbon agriculture. In short, technology facilitates knowledge of carbon stocks in the soil and can therefore serve as a tool to help reduce the risk exposure of agricultural crops, boosting the adaptive capacity and competitiveness of production systems in an increasingly dynamic environment.

In summary, infrared spectroscopy through the SpecSolo platform represents a revolution in the way soil analysis is carried out, promoting a transition towards sustainability, digitalization and valorization of carbon in the soil. Its integration with modern methodologies and national public policies helps position Brazil as an important player in the use of clean and intelligent technologies for environmental monitoring and the strengthening of carbon markets to benefit Brazilian society.

¹ Available at: www.specsolo.com.br/antiga_pg_specsolo_scan.

² Available at: www.embrapa.br/solos/paqlf.

Innovative solutions for monitoring soil density

Soil density (Ds) varies due to a number of factors that include soil mineralogy, particle distribution and shape (the packing effect), as well as land use and management, topography, drainage and climatic conditions, which influence the accumulation of organic matter, pore size distribution, aggregation, and soil structure. For this reason, Ds exhibits high spatial and temporal variability across the landscape and at different soil depths.

Over the past two decades there has been growing interest in predicting Ds, an essential parameter for quantifying carbon and nutrient stocks in the soil which is also fundamental for modeling various soil processes. One alternative approach that costs significantly less than the conventional procedure for determining Ds is the use of mathematical prediction models. This prediction has been based on more readily available soil attributes; some models are already available and have been calibrated through tests carried out by Embrapa and its partners.

Another potential approach to circumvent the difficulties involved in collecting soil samples to obtain Ds is the use of automatic probes (whether operated by machines or manually). This technique is being tested at various Embrapa research units, with promising results. The potential of this technique will be discussed below in the future prospects section.

Development of pedotransfer equations

The concept of pedotransfer function (PTF) refers to methods that “transfer” available data to estimate soil properties or other variables that are difficult to measure but are necessary for modeling or evaluating soils. These PTFs make it possible to estimate Ds based on other soil

attributes, such as granulometry (sand, silt, and clay fractions), pH, sum of bases, cation exchange capacity (CEC), and organic carbon content. The values of these attributes can be obtained from soil samples collected via coring, without the need to dig trenches.

Various studies have been conducted to develop PTFs, commonly using sand, silt, clay, and C content as predictor variables with different linear and non-linear regression methods and, more recently, machine learning techniques. Accurate estimates of Ds are fundamental for reliable application in different contexts, such as quantifying soil carbon stocks, assessing soil compaction, and hydrological modeling. When using Ds estimates obtained by PTFs to replace data obtained by direct methods, it is essential to assess the accuracy of the predictive model used. Table 4.2 presents a summary of the literature on PTFs developed to estimate Ds, highlighting their scope (local or national), associated accuracy expressed by root mean square error (RMSE), as well as the type of model and predictor variables used.

Models with a local scope have been developed for micro-basins (Souza et al., 2016; Sevastas et al., 2018), soil classes (Beutler et al., 2017; Cunha et al., 2017), regions with specific climatic characteristics (Al-Quinna; Jaber, 2013), biomes (Bernoux et al., 1998; Tomasella; Hodnet, 1998), and land uses and covers (Barros; Fearnside, 2015; Choudhury et al., 2023), among others. In general, the models developed on a national scale involve more complex relationships between soil properties and Ds on broader scales that incorporate multiple land uses, different geomorphological domains, and biomes. Another relevant point is that methods based on machine learning performed better than conventional regression methods, such as multiple linear regression (MLR), multiple non-linear regression (MNLR) and non-linear least squares (NLLS).

Table 4.2. Summary of work to develop pedotransfer functions for soil density in Brazil and other countries.

Work	Country	Scope	Method ⁽¹⁾	RMSE ⁽²⁾	Predictor variable ⁽³⁾
Schillaci et al. (2021)	Italy	Local	ANN	0.07	Clay, sand, SOC, pH, clim, rel
Obidike-Ugwu et al. (2023)	Nigeria	Local	MLR	0.075	Sand, SOC, q
Zheng et al. (2023)	China	Local	SVMR	0.08	Clay, silt, sand, SOC
Botula et al. (2015)	Congo	Local	k-NN	0.09	Sand, silt, clay, SOC, Fe, Al
Choudhury et al. (2023)	India	Local	ANN	0.09	Sand, silt, SOC
Gomes et al. (2017)	Brazil	Local	MLR	0.11	Clay, SOC, pH, SB, Al
Sevastas et al. (2018)	Greece	Local	MNLR	0.11	Clay, silt, sand, SOC
Al-Qinna and Jaber (2013)	Jordan	Local	MLR	0.13	Sand, SOC
Botula et al. (2015)	Congo	Local	MLR	0.13	SOC, Fe, Al
Souza et al. (2016)	Brazil	Local	RF	0.15	Clay, SOC, pH, SB, env
Palladino et al. (2022)	Italy	Local	RF	0.16	Clay, silt, sand, SOC, pH, CaCO ₃ , rel
Santos et al. (2025)	Brazil	National	RF	0.12	Clay, sand, SOC, clim, rel, others
Han et al. (2012)	China	National	MLR	0.13	Clay, SOC, N
Ramcharan et al. (2017)	USA	National	RF	0.13	Clay, sand, SOC, pH, env, others
Reis et al. (2024)	Brazil	National	MLR	0.14	Clay, fine sand, SOC
Nanko et al. (2014)	Japan	National	NLLS	0.14	SOC
Boschi et al. (2015)	Brazil	National	MLR	0.18	Clay, sand, SOC, Ph
Abdelbaki (2018)	USA	National	MLR	0.18	SOC
Benites et al. (2007)	Brazil	National	MLR	0.19	Clay, SOC, SB
Chen et al. (2024)	Europe	National	RF	0.19	Clay, sand, SOC, pH, N, clim, rel
Heuscher et al. (2014)	USA	National	MLR	0.19	Clay, silt, SOC, q
Beutler et al. (2017)	Brazil	National	MLR	0.22	Clay, SOC

⁽¹⁾ ANN: artificial neural networks; MLR: multiple linear regression; SVMR: support vector machine regression; k-NN: k nearest neighbors algorithm; MNLR: multiple non-linear regression; RF: random forest; NLLS: non-linear least squares.

⁽²⁾ RMSE: root mean square error.

⁽³⁾ SOC: organic carbon; q: soil moisture; Fe: iron; Al: aluminum; SB: sum of bases; clim: variables related to climate; rel: variables related to relief; env: environmental variables; others: additional numerical and categorical variables; N: nitrogen.

In general terms, it has been observed that in soils from temperate regions, carbon is the main variable explaining Ds, and is often the only variable selected in the PTFs of these regions (Nanko et al., 2014; Abdelbaki, 2018). On the other hand, in tropical regions characterized by highly weathered soils, soil texture is more relevant in Ds prediction models, with carbon

as the second most important variable, as demonstrated in the studies by Benites et al. (2007), Reis et al. (2024), and Santos et al. (2025). The main limitation of the PTFs that use granulometric variables, SOC, and other soil physicochemical variables is that these variables are expressed on a gravimetric basis, and capture only part of the effects on Ds.

One promising approach to overcome this limitation consists of incorporating other variables (both numerical and categorical) that add knowledge to the predictive model through information related to soil structure. These variables include the silt/clay ratio, which tends to increase with the soil's aggregation capacity; the clay/sand ratio, associated with greater cohesion and lower porosity; and water-dispersed clay content and the flocculation index, where high values indicate low structural stability. Furthermore, topographic and relief-related variables such as slope, altitude, topographic moisture index, curvature of the terrain, and slope orientation (aspect) also influence the structural quality of the soil by affecting processes such as erosion, redistribution of particles, accumulation of organic matter, and variations in the water regime across the landscape.

The approach of using numerical and categorical variables together has gained prominence in recent years, as shown in studies such as Santos et al. (2025). However, for effective application it is essential to have the geographical coordinates of the data. Another important aspect in the development of models that can be applied on a national scale is the need for a broad and representative database that takes into account the diversity of the main soil classes, textural classes, biomes, climatic zones, and different forms of land use and cover, and where possible, the length of time the land has been used, especially for structured clay soils that tend to become compacted with agricultural use.

Innovative solutions for monitoring greenhouse gas flows in agriculture

Quantifying GHG emissions in agriculture is essential to understand the environmental impacts of agricultural activities and develop

mitigation strategies. In the context of Embrapa's research networks (Fluxus, Saltus, and Pegasus) and other research initiatives, the use of manual static collection chambers has been the main technical solution available to date for monitoring the flow of nitrous oxide (N_2O) and ammonia volatilization (NH_3), following international criteria and ensuring comparability between data obtained in Brazil and global studies.

During the process of directly determining GHG flows, sampling is performed using closed static chambers, a method accepted by the international scientific community as long as technical criteria are observed. These chambers are installed in the soil and capture the gases emitted over time. Samples are taken from the chambers at regular intervals, permitting analysis of variations in gas concentration. The GHG samples collected are usually analyzed by gas chromatography, using specific detectors for each gas.

More recently, techniques for measuring GHG concentrations using laser spectroscopy have been applied to measure carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). This method is based on absorption spectroscopy, namely the interaction between laser light and gas molecules, considering that different gases absorb radiation at specific wavelengths. The technique itself is commercial; the approach here will be to adapt these techniques for the continuous monitoring of GHG flows in agriculture.

Adapting static chambers to monitor direct emissions under national conditions

The main aspects of static chamber design have already been detailed in national (Zanatta et al., 2014; Alves et al., 2017) and international protocols (Parkin; Venterea, 2010; Zaman et al., 2021). The main models of static chambers adapted for use in studies in Brazil for direct measurement of GHG can be seen in Figure 4.4.



Figure 4.4. Types of chambers and materials available for fabrication: (A) cylindrical shape with galvanized steel base and PVC top; (B) cylindrical shape with galvanized steel base and polyurethane top covered with thermal insulation; (C, D) cylindrical shape with PVC base and top; (E) rectangular shape with galvanized steel base and polyethylene top; (F) square shape with galvanized steel base and top; (G) rectangular shape with aluminum base and top; (H) rectangular shape with galvanized steel base and polypropylene top covered with thermal insulation; (I) rectangular shape with galvanized steel base and top; and (J) rectangular shape with galvanized steel base and polyethylene top.

Photos: Josiléia Acordi Zanatta (A, B, J e L), Falberni De Souza Costa (C), Bruno José Rodrigues Alves (D, E, F e K), Cimélio Bayer (G) e Michely Tomazi (H e I).

Source: Adapted from Zanatta et al. (2014).

Determining the shape of the chamber and the material to build it with tends to be connected, since the goal is to adapt industrialized materials to make them easier to build and handle in the field, and reduce costs while simultaneously meeting the technical specifications for the chamber as well as the crop to be monitored. Inexpensive materials make it possible to increase the number of repetitions in the field; in contrast, very heavy chambers are difficult to handle in the field and may require large teams for sampling, depending on the frequency retired.

The criteria to be observed when developing projects with static chambers are as follows:

Dimensions and materials: Chambers must be made of materials like PVC or aluminum that are inert to the gases being measured, to avoid reactions that might alter the results. Height and internal volume are optimized to minimize environmental changes inside the chamber.

Controlled ventilation: Small vents ensure balanced internal pressure without altering the concentration of gases.

Proper sealing: The seal between base and top can be made of channels filled with water or inert rubber to prevent leakage.

Sampling system: Includes collection ports connected to sealed syringes or vials for subsequent analysis in the lab.

Although this method is widely used, it has limitations, such as the need for manual sampling and the possibility of distortions due to the influence of environmental conditions inside the chamber. With this difficulty in mind, researchers from Embrapa Forestry, in partnership with the Technological University of Paraná, developed a prototype of semi-automatic equipment (Figure 4.5) capable of taking samples directly from vials that were emptied after the chambers were closed. The prototype was developed based on an embedded system to control pumps and pneumatic valves for sample collection via a remote app interface, for remote interactions via Bluetooth and easy sharing of the data obtained. The technical functionalities of the complete system have been tested on the lab bench and in the field (Figure 4.5), with successful results described in Libel et al. (2021).

Collection chambers have been the main technical solution available up to this point to measure GHG flows in agriculture, guaranteeing the standardization and comparability of the results obtained. Despite the operational and

Photos: Josiléia Zanatta

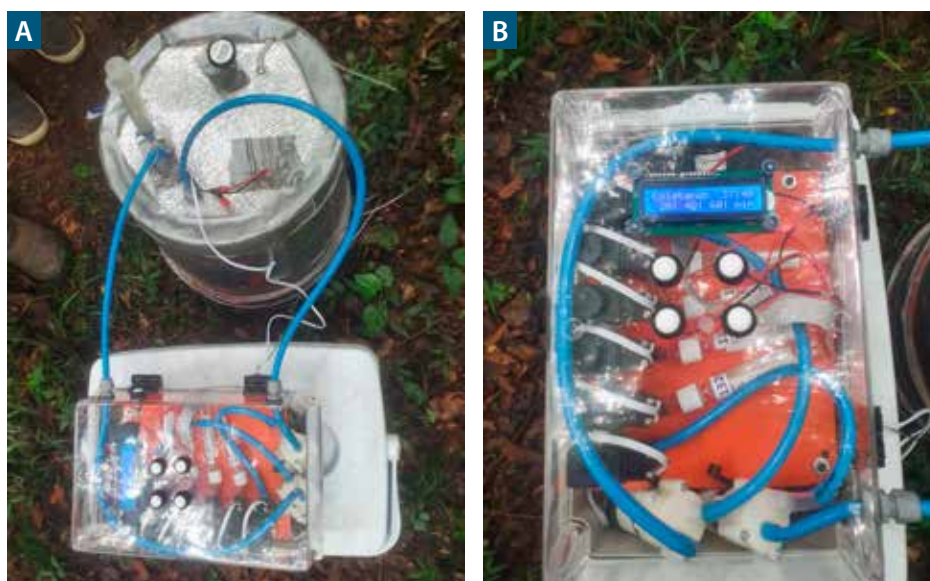


Figure 4.5. Prototype of a semi-automatic system for collecting air samples via static chambers to monitor the flow of greenhouse gases.

methodological limitations, their use has followed internationally established scientific protocols, ensuring the reliability of the data generated. Recent technological advances are already pointing towards more automated and efficient solutions, bringing with them new possibilities for innovation in agricultural GHG monitoring.

Adaptation of the laser spectroscopy technique to measure soil greenhouse gas flows

The measuring equipment incorporates different techniques based on direct absorption spectroscopy, which quantifies the attenuation of a laser beam with a wavelength specific to the gas being monitored. Configurations may vary, such as cavity ring-down spectroscopy (CRDS), cavity attenuated phase shift spectroscopy (CAPS), and off-axis integrated cavity output spectroscopy (OA-ICOS), in which detection of the attenuation rate occurs through the loss of energy from a laser pulse confined within a highly reflective optical cavity, where the gas aspirated from the environment is present. The equipment records the intensity of light before and after it

passes through the gas. The difference in intensity (attenuation) is proportional to the concentration of the gas in the optical path.

One major advantage of laser spectroscopy over gas chromatography is its high precision, even at very low concentrations of the GHG, such as nitrous oxide (N_2O). In addition to highly precise measurements, it offers rapid response time. The ability to operate in portable mode is especially useful for studies in remote areas, since there is no need to store or transport samples (Figure 4.6), or even in experiments that require very frequent measurements (Figure 4.7). In this case, the incubation chamber works in closed dynamic mode; in other words, the air circulates through the chamber past the equipment, which records the increase in GHG concentration over time. The angular coefficient of the line, adjusted to the time and concentration data, results in the flow of the gas emitted into the atmosphere.

Multi-channel models can be used to monitor a large number of treatments simultaneously. In the system depicted in Figure 4.7, 15 sampling points are monitored every 2 hours (Ibarr et al., 2021). In addition to spatial coverage, the

Photos: Bruno Alves



Figure 4.6. Off-axis integrated cavity output spectroscopy (OA-ICOS) analyzer for monitoring nitrous oxide (N_2O) and methane (CH_4) flows in soil planted with soybeans, in a greenhouse (A) and in the field (B), both at Embrapa Agrobiologia.



Figure 4.7. Cavity ring-down spectroscopy (CRDS) analyzer for monitoring greenhouse gas flows in soil planted with forest species in a greenhouse (A) and in the field (B), both at Embrapa Forestry.

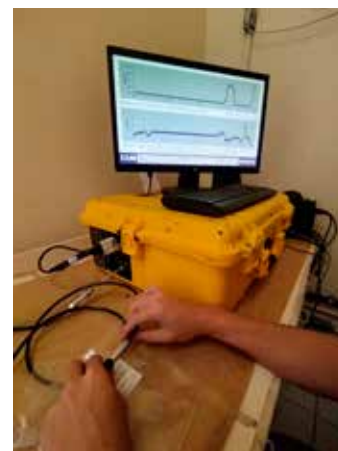
robustness of the concentration values obtained is undoubtedly the greatest advantage of these laser systems, since gas concentration is measured every 2 seconds and the average concentration of the gas of interest derived from at least 30 measurements. This robustness makes it possible to estimate the flow with fewer collection times (Ibarr et al., 2021).

In general, equipment using this technique operates in dynamic systems. In static mode, the chamber volume must be greater than 50 L to avoid significant negative pressure effects, since one disadvantage of this technique is that it requires samples with larger volume: up to 50 times larger than those used in gas chromatography. Sensitivity to high temperatures presents a problem in tropical environments, which during long routines in the field and especially in summer can mean frequent interruptions due to overheating and the need to shut down. Humidity in the air can also be a problem, but can be avoided by using filters at the external air intake. The equipment is expensive (over USD 180,000), which may limit more widespread use in the country. On the other hand, the robustness of the equipment, which requires practically no maintenance and also does not need calibration gases, greatly reduces the

operating costs for research. Technical assistance in this area is still in its infancy in Brazil.

Benchtop mode is an interesting option where the equipment can be operated similar to a gas chromatograph, avoiding exposure to dust, and high humidity and temperatures. It has been used at Embrapa Agrobiology to study flows of N_2O and CH_4 in the soil with the closed static chamber technique. In this case, the sample inside the chamber is removed at every incubation time via a 200 mL syringe attached to a Tedlar-type sample bag (made of highly impermeable plastic material specifically for environmental samples), which provides a volume sufficient for the OA-ICOS laser analyzer (Figure 4.8). The bags replace the syringes and chromatography vials typically used for chromatography sampling and analysis; they are expensive, however (~USD 50.00 per unit), even though they can be reused.

Experience using laser spectroscopy equipment shows that a great deal more sensitivity and precision can be attained, and that even very small soil gas flows can easily be measured. This makes it possible to reduce the number of samples during incubation, and even the time between samples, making the experiment more efficient.



Photos: Bruno Alves

Figure 4.8. Transferring air from the chamber to the Tedlar bag using a 200 mL syringe. Note that an initial aspiration of 10 mL is carried out for flushing, followed by aspiration and transfer of 200 mL of air from the chamber into the bag. The bags are then taken to the laboratory and individually connected to the laser analyzer, where nitrous oxide (N_2O) and methane (CH_4) concentrations are analyzed in approximately 1.5 minutes

Innovative solutions for monitoring greenhouse gas emissions from animals

Livestock farming has been associated with high greenhouse gas (GHG) emissions. At times during discussions on GHG mitigation in ruminant production systems, the relationship between feed efficiency, adequate animal performance, and GHG emissions seems incompatible. However, there are different possibilities for creating sustainable production systems while

simultaneously making a profit and producing meat and milk that meet consumer demands and ensure profitability for the farmer, depending on the animal type and species.

Two technologies are particularly important from this perspective: CH_4 emission proficiency testing for cattle, and GHG measurement services for small ruminants using respirometry chambers.

Bovine enteric methane emission proficiency test

This technology called Prova de Emissão de Gases (Proof of Gas Emission, PEG), was launched by Embrapa Southern Livestock and is used to measure the methane gas emitted by European breeds of cattle. The goal is for livestock farmers to be able to use this information to help select breeding stock, combining weight gain and production with lower GHG emissions. PEG testing serves as a tool to improve the efficiency of livestock farming and reduce GHG emissions, and is part of a larger effort to understand and

reduce the impact of livestock farming on the climate, solving one of livestock farming's sustainability challenges. It is used to identify animals with lower methane emissions, which can be an important factor in genetic selection, indirectly contributing to the establishment of herds with greater production efficiency and less environmental impact.

The methodology for evaluating enteric methane emissions is now part of the service offered by Embrapa Southern Livestock to assess performance and feed efficiency. The evaluation is conducted on breeding stock of European breeds such as Angus, Charolais, Braford, and Hereford, which are sent to the research unit every year. The process uses the sulfur hexafluoride (SF₆) tracer gas technique, as described in a protocol previously established by Embrapa (Berndt et al., 2014). The test seeks to identify the animals with the lowest methane emissions for each kilo of food consumed and per kilo of live weight produced. Enteric methane is one of the main GHGs emitted by livestock farming, and research is working to reduce this environmental impact (Genro et al., 2023).

In addition to combining methane emissions with field tests of feed efficiency, Embrapa Southern Livestock intends to conduct genetic validation of this trait, contributing to a greater understanding of methane production by animals. Livestock production is the main source of methane emissions in Brazil; from the viewpoint of national competitiveness, reducing methane emissions in livestock production and improving feed efficiency rates directly improves the country's image. Preliminary results indicate lower emissions per animal per year than those recommended by the IPCC guidelines (Genro et al., 2023), creating a qualification for these animals and making direct contributions to the decarbonization of Brazilian livestock.

Greenhouse gas measurement service in small ruminants at the Semi-Arid Respirometry Laboratory (LARESA)

In the context of climate change, tests to assess ruminant metabolism using respirometry also help measure GHG emissions, making it possible to develop efficient feed management techniques to mitigate these gases in livestock production systems and supporting development of feed and supplements that provide maximum feed efficiency.

These emissions are measured in respirometry chambers over periods of 21-24 hours per animal. This technique is the gold standard that even can be used to calibrate other equipment, with a view to using other techniques that are also accessible and scalable for field data collection. At Embrapa Goats & Sheep, this technique has been studied and improved for over 16 years. Initial efforts were directed towards equipment calibration to ensure adequate measurements, especially of enteric methane and carbon dioxide. Appropriate models are continually being developed, making it possible to evaluate small ruminants on pasture. Another approach includes the use of portable respirometry chambers that can be transported to the field, as well as the strategy of moving the animals at specific times of day to the locations where the respirometry chambers are installed, allowing measurements to be taken in short periods of time (30 to 60 minutes).

From an economic perspective, this technology has the potential to transform the sector by enabling new feeding practices, providing financial benefits to producers by reducing costs and increasing production efficiency. GHG mitigating diets in association with breed selection for feed efficiency and lower GHG emissions, for example, can be applied in practice by small ruminant producers, field technicians, and nutritionists. An experimental

trial at Embrapa Goats & Sheep was able to determine that the use of diets with bioadditives that manipulate rumen fermentation led to a 52% reduction in CH₄ emissions compared to traditional diets. It is therefore possible, based on the assessments made using this methodology, to develop more productive and sustainable livestock systems that help maintain ecosystems in a way that is adaptable to climate change and which progressively improve the efficiency of land and soil use. The research carried out at the Laboratório de Respirometria do Semiárido (Semi-Arid Respirometry Laboratory, LARESA) has resulted in groundbreaking publications and filing of a specific patent on the use of GHG mitigating bioadditives, providing opportunities to interact with both domestic and international companies that produce food inputs and GHG mitigating bioadditives for ruminants (Rogério et al., 2019a, 2019b, 2022; Costa et al., 2020, 2021; Oliveira et al., 2020; Alves et al., 2024).

The resulting instrumentation and methods have been applied in long-term field experiments at Embrapa and in privately owned areas, yielding highly promising results. Advances in research and the growing market demand for GHG (enteric methane and CO₂) analysis have driven the official launch of the service, which will take place at VICTAM LatAm 2025,³ the largest international trade fair and congress for technology, equipment, ingredients, and additives in this production chain, with a focus on the animal nutrition and grain processing industries. There may be some limitations to the use of the technique in relation to individual variations, but these can be overcome by the need for more numerous repetitions, depending on the variability between readings.

The GHG measurement service for small ruminants has made a significant contribution to national competitiveness in the agricultural

sector. In Brazil, there are few structures and services that carry out this type of measurement. By offering this service, Embrapa is making its qualified research environment available to serve as the conduit for measuring the real emissions from livestock farming, adopting sustainable production practices, achieving maximum feed and production efficiency, and reducing risks for producers and industry.

The development of specific mathematical models for quantifying emissions provides greater security and decreases risk for this activity, resulting in added value and increased competitiveness. For the industry, it is a guarantee that the products are more sustainable. For producers, it allows them to have more knowledge about their production, generating additional income and permitting them to enter new markets that value sustainable agricultural practices, strengthening Brazil's position in the global market.

The service can be perceived by those involved as an innovation capable of providing robust data and supported by qualified research which can clarify that Brazilian livestock systems involve environmental sustainability, based on management strategies aimed at maximum efficiency and GHG mitigation. This translates notably into the generation of specific GHG mitigation indices per animal product produced (kilo of carcass or liter of milk, for example), allowing traceability of sustainable production initiatives.

Innovative solutions for monitoring carbon in trees

Traditional forest inventories involve measuring the biophysical parameters of trees in sample plots, such as diameter at breast height (DBH) and total height (Corte et al., 2020). This data is then used in specific allometric equations for species or groups of species to estimate the

³ www.embrapa.br/caprilos-e-ovinos/sead.

biomass of each tree, which is then extrapolated to the total area (Machado et al., 2025). Although field inventories can provide highly accurate estimates at local scales, they are expensive, time-consuming, and laborious, especially for studies that cover large areas or regions that are difficult to access (Corte et al., 2020; Costa et al., 2021). In Brazil, the Inventário Florestal Nacional (National Forest Inventory, IFN) uses this methodology to obtain information on forest resources at a national level. Studies such as Machado et al. (2025) established biomass equations and quantified biomass and carbon stocks in subtropical forests in Paraná, using allometric data collected in the field and preexisting equations for larger trees.

The quantification of carbon stocks is often derived from biomass estimates. For example, aboveground biomass (AGB) in forest ecosystems and agroforestry systems is fundamental for understanding the global carbon cycle, assessing ecosystem health, determining primary productivity, and monitoring biodiversity (Sinha et al., 2016; Machado et al., 2025).

Remote sensing techniques for estimating biomass

The dynamics of growth and mortality, along with biomass losses due to fires or deforestation, directly influence GHG concentrations in the atmosphere (Costa et al., 2021; Machado et al., 2025). Estimating aerial biomass, especially repeatedly and on a large scale, is crucial to develop strategies to mitigate and adapt to climate change in the agriculture and forestry sector that include sustainable forest management, reforestation, and implementation of integrated systems like ICLF (Corte et al., 2020; Lima et al., 2022).

Remote sensing makes it possible to acquire vegetation data on much larger spatial and temporal scales, overcoming some of the

limitations of field inventories (Costa et al., 2021; Lima et al., 2022). Different types of sensors and platforms can be used to estimate aerial biomass; these include passive optical sensors like those used on the Landsat and Sentinel-2 satellites, and active sensors such as light detection and ranging (LiDAR) and radio detection and ranging (RADAR). Multispectral optical data makes it possible to calculate vegetation indices (such as NDVI, SAVI, and EVI) that are related to vegetation density, canopy cover, and biomass (Ceddia et al., 2017; Zhou et al., 2022; Bartsch et al., 2025). Minihoni et al. (2021), in a study carried out in agricultural areas in southeastern Brazil, demonstrated that multitemporal analysis of spectral indices derived from Sentinel-2 images can be used to assess soil organic carbon and indirectly provide information on vegetation biomass. However, direct estimation of aerial biomass using optical data alone can be limited by signal saturation in areas of high biomass and sensitivity to atmospheric conditions (Corte et al., 2020). While LiDAR and RADAR involve a similar basic principle (sending and receiving energy pulses), they use different technologies and have different characteristics.

LiDAR can provide detailed information on tree height, canopy structure, vegetation density, and wood volume, parameters that are strongly correlated with biomass (Costa et al., 2021). Studies conducted in Brazil, such as D'Oliveira et al. (2020) in the Amazon and Machado et al. (2025) in subtropical forests, show the potential of airborne LiDAR on board unmanned aerial vehicles (UAVs, popularly known as drones) to estimate aerial biomass with high precision. Machado et al. (2025) used allometric equations and forest inventory data to validate biomass estimates obtained with LiDAR. In tropical savanna ecosystems (Cerrado), Costa et al. (2021) and Machado et al. (2025) demonstrated the ability of UAV-borne LiDAR to estimate total aerial biomass (including trees, shrubs, and undergrowth), highlighting the importance of this technology for carbon monitoring.

The combination of optical remote sensing and LiDAR data can overcome the limitations these individual techniques present, providing more accurate and robust aerial biomass estimates (Zhang et al., 2019; Petropoulos et al., 2025). The integration of canopy surface information obtained by optical sensors with vegetation structural data provided by LiDAR allows for a more complete characterization of biomass (Zhang et al., 2019). Kulawardhana et al. (2014) and Zhang et al. (2019) demonstrated that multiple regression models using combined variables from LiDAR and multispectral vegetation indices perform better in predicting plant biomass than models based on just one of these data sources.

Embrapa has made consistent contributions to the estimation of aerial biomass in Amazonian tropical forests using aerial LiDAR and UAV data, involving innovative methodologies for forest inventory in the Amazon (D'Oliveira et al., 2020) as well as other biomes (Dalla Corte et al., 2022). One example is Embrapa's Netflora, which uses AI algorithms trained on a database of 40,000 hectares mapped by drones to semi-automate the planning and execution of precision forest inventories and spatialize carbon emissions from different land uses in the Amazon. Netflora provides a protocol for acquiring drone data to detect forest species and training AI algorithms according to the phenological calendar to recognize forest species using orthophotos. In this way, it strengthens automation in initial inventories and expands monitoring capabilities for aerial biomass and carbon stocks (Cunha et al., 2019; Queiroz et al., 2023) in precision forest management systems.

To convert aerial biomass into carbon stocks, it is generally assumed that a fixed proportion of the dry biomass (typically around 50%) is composed of carbon (Machado et al., 2025). In this way, estimates of AGB (in tons per hectare or gigagrams) can be multiplied by a conversion factor to obtain equivalent carbon stocks.

Machado et al. (2025) estimated carbon stocks in subtropical forests in Paraná using this approach.

Estimating root biomass (below-ground biomass, or BGB) is more challenging, due to the difficulty of directly observing the subsoil. Traditionally, BGB is estimated using root-to-shoot ratio factors (R), which are multiplied by AGB to obtain an estimate of underground biomass (Costa et al., 2021). These R factors can vary widely depending on the species, plant age, environmental conditions, and type of ecosystem (Costa et al., 2021). As a result, the accuracy of BGB estimates based on R factors strongly depends on the availability of specific and representative factors for the study area. Some studies have sought to establish empirical relationships between parameters for aerial components such as DBH, height, crown area, and root biomass using destructive methods or techniques like GPR (Adão et al., 2025), but generalizing these relationships still remains a challenge. Basuki et al. (2009) and Machado et al. (2025) developed allometric equations to estimate AGB and BGB in low-altitude tropical forests, demonstrating the complexity of the relationship between the aerial and subterranean components.

Notable advantages of remote sensing and combined approaches (optical and LiDAR) over traditional forest inventories include:

Extensive spatial coverage: contributes to assessment of biomass over large areas, including remote and difficult-to-access regions.

Repeatability and temporal monitoring: make it possible to monitor changes in biomass over time in response to natural events (growth, fires, storms) or human activities (management, deforestation).

Reduced costs and time: may be more efficient in terms of time and cost compared to intensive field data collection over large areas.

Detailed structural information (LiDAR):

provides data on vegetation height and vertical structure, which are strongly related to biomass.

There are also limitations and difficulties associated with the use of remote sensing to estimate aerial biomass, which will be dealt with in the section on future prospects.

The use of remote sensing techniques, especially LiDAR and the combination of optical and LiDAR data, represents a significant advance in data collection for estimating aerial biomass and, in turn, carbon stocks in tree components. These approaches offer the scalability and repeatability needed for large-scale carbon monitoring, contributing to the development of effective climate change adaptation and mitigation strategies in agriculture and forest ecosystems, including the Brazilian context (Costa et al., 2021; Minihoni et al., 2021; Machado et al., 2025). However, it is essential to recognize the limitations and invest in the development of robust methodologies to calibrate, validate, and integrate these techniques with field data in order to obtain increasingly accurate and reliable estimates of aerial and underground biomass.

The SIS family

The SIS family is a set of software programs to support forest management of introduced or exotic species. Embrapa has been developing forest management software since 1988, initially for monocultures, and since 2016 also for ICLF systems. There are currently 25 software applications that are widely used by the Brazilian forestry sector. With these programs it is possible to make forecasts of wood production under present and future conditions, for each climate and soil condition, carry out economic analyses, and then implement the best planting alternative in the field. They permit simulation of how the forest plantation will grow and produce according to the management regimes indicated by the user, and also calculate the carbon captured by the trees.

The models were created using data from continuous inventories and experiments conducted by Embrapa itself and by forestry companies, which provided their forest growth and production inventory databases and tested the software. The software uses the Delphi programming language and is called SIS plus the common name of each specific genus or species in question. The software includes species of *Pinus* and *Eucalyptus*, as well as black acacia, Paraná pine (*Araucaria angustifolia*), bracatinga (*Mimosa scabrella*), Australian cedar, African mahogany, and teak. These solutions provide information to optimize production and expand the producer's income.

Unlike agricultural crops, each individual stand requires specific management to optimize forest production. Thinning practices of different types, intensities, and times and variations in the age at final harvest can affect production. The effect of thinning can also vary, depending on factors such as the industrial use of the wood, site quality (in terms of soil and climate), genetic material, spacing, and plant density. Altering one of these factors changes the ideal management regime and, in turn, the productive potential of the forest. Thinning is one of the most important practices in forest production. Its importance stems from its direct relationship with tree growth. As trees grow in reforestation, competition between them for water, light and nutrients increases, and thinning is conducted to reduce excess competition. The SIS programs make it possible to simulate the effects of thinning and to test any management regime in the stands. To operate the SIS simulators, the user provides the forest inventory data and the software predicts growth and production, indicating how much wood the forest will produce at any given age.

The technology helps define silvicultural treatments such as pruning, immediate or future thinning, or continuing until the final harvest,

and considers factors and parameters that lead to optimized forest production and income, depending on the objective. This is a clear example of how technology boosts the efficiency of forestry production, ensuring competitiveness in producing wood products from the forest. The use of software to optimize forest management contributes to the sustainability of the sector, avoiding the waste of resources and promoting efficient management of natural resources.

Another important aspect is that this technology helps reduce agricultural risk, since the simulation makes it possible to create scenarios while considering soil type and climate. This allows users to connect forest production and investments in silvicultural techniques and treatments in line with the site's carrying capacity. Precision forestry makes it possible to manage the forest based on science, making the best use of the site and maximizing income.

The SIS have been well-received by the public, especially in terms of usefulness in strategic planning and forest management. The SIS software helps producers make decisions about planting, thinning, and harvesting, optimizing production and increasing income. Every year there are 4,000 downloads of SIS family software. Embrapa, which is responsible for these products, emphasizes the importance of its ease of use and the ability to simulate various scenarios, allowing producers to analyze different forest management strategies.

Future prospects

Considering the challenges posed by climate change and intensified by GHG emissions, it is crucial for Brazil and the productive sector to monitor and quantify these emissions, along with the carbon stored in different compartments of the environment. Brazil, with its vast territory and strong agricultural sector, plays an important role

in both GHG emissions and mitigation. In order to fulfill its international commitments (such as the Paris Agreement) and so that companies and farmers can improve their practices and even be rewarded for sustainable actions, it is essential to be able to measure and monitor carbon storage in the soil and forests and the quantity of GHG emissions and removals, especially in agriculture.

Collecting field data for this purpose, in a country of Brazil's size, is an enormous task. To meet this challenge, Embrapa and its partners have been working to develop and adapt techniques and tools that are more accessible and can be applied on a large scale. The goal is to collect data more efficiently and at a lower cost than traditional methods, which often require significant effort and qualifications and may be invasive. While progress has been significant, there are still challenges to overcome, and areas that need improvement.

Although these new techniques have advanced significantly, there are still aspects that must be refined or improved so that monitoring of carbon stocks and GHG flows in the field (along with other essential variables) can become completely scalable, efficient, and reproducible, permitting the generation of accurate metrics throughout the country.

As for monitoring soil carbon, which is just as important a component as carbon in vegetation, innovative techniques such as the AgLIBS AI and SpecSolo platforms represent a major step forward. They promise faster and cheaper analysis, without the use of chemical reagents and with less waste, making it easier to create carbon and nutrient maps. The acceptance of these techniques to certify carbon credits in voluntary markets is an important step, but standardization and validation on a large scale remain an ongoing task. Integration with other systems to generate real-time information (especially in the case of AgLIBS AI), such as the concept of an autonomous "agricultural rover," is still a prospect to be consolidated in the future.

The “agricultural rover” would be able to roam the countryside, monitoring the soil in real time and connecting this information directly to agricultural operations. This will lead to more intelligent input use, providing economic and environmental benefits.

Remote sensing techniques such as RADAR/SAR and ground penetrating radar (GPR) are also important future prospects for monitoring soil carbon and root biomass. RADAR/SAR makes it possible to cover large areas and operate in adverse weather conditions, while GPR is useful for investigating subsoil structure and roots in a non-destructive manner. However, the relationship between the signal from these technologies and soil carbon is not direct and can be influenced by other factors, requiring complex models. GPR has penetration depth limitations in clayey or wet soils, and specialized knowledge is required to interpret the data. Estimation of root biomass with GPR is still under development. Using machine learning to integrate this data with other information is seen as one way to improve accuracy.

Another crucial point for quantifying carbon stocks in the soil is determining its density. Traditional methods for measuring soil density are laborious, and limit application over large areas. One promising alternative lies in pedotransfer equations (PTFs), which allow density to be estimated from other soil characteristics that are easier to obtain, such as granulometry (sand, silt, clay) and carbon content. Although models based on machine learning perform well, one aspect that requires improvement is the incorporation of variables that better capture the effects of soil structure and landscape conditions (such as relief and climate), which also influence density. Furthermore, developing accurate PTFs at a national level, considering the enormous diversity of soils in Brazil, is a complex challenge that requires large databases and advanced processing methods. Automated probes for collecting

undeformed soil samples are also being tested as a way to hasten soil density diagnostics, avoiding the need to dig trenches. While these probes offer great potential to replace traditional methods and permit large-scale collection, systematic studies are still required to validate their accuracy and correspondence with standard methods in different soil types, moisture conditions, and agricultural uses.

Static chambers are the most widely used technique around the world to monitor the flows of GHG released by soils in agriculture. But they involve complex and labor-intensive field collection, which limits the number of measurements and the frequency of monitoring, and makes it difficult to carry out more comprehensive studies over space and time. Semi-automatic sample collection systems have been developed to expand collection capacity in the field. The laser spectroscopy technique for measuring GHGs in soil permits quick responses and portable operations, but is sensitive to high temperatures and requires larger sample volumes than gas chromatography. Furthermore, technical assistance for equipment based on laser spectroscopy is still nascent in Brazil.

Measuring GHG emissions from animals (such as enteric methane from cattle and small ruminants) also presents challenges in terms of scale. Although respirometry chambers are considered the “gold standard” for precise measurements, they are laborious and restricted to a small scale. Making this measurement accessible and scalable for large numbers of animals and direct use on farms still remains an obstacle. Qualified services for this measurement are starting to become available in Brazil, using the SF₆ tracer gas technique. This type of service and the environments in which it is offered need to be expanded in order to cover the main conditions involved in the production systems present in the country, and for different categories of animals, breeds, age, etc.

Finally, quantifying the carbon stored in tree components, which is essential for understanding the carbon cycle, also faces challenges of scale. While traditional forest inventories are locally accurate, they are expensive and slow for large areas. Remote sensing, including LiDAR and satellite imagery, offers a more time- and cost-efficient alternative for monitoring biomass on a large scale, but has some limitations, such as signal saturation in dense areas (in optical data) and the cost of acquiring and processing LiDAR data. The creation of techniques like Netflora, which are based on artificial intelligence and sensors, to support forest inventories and map emissions requires collection of specific data, such as drone images. It is also essential to train models using representative, robust databases in order to ensure accuracy in the analyses.

All in all, while Brazil is making progress in developing and adapting innovative techniques and tools to collect and monitor field data for climate and environmental management in agriculture and forestry, much work still remains to make these solutions fully accessible, scalable, and validated in all of the country's diverse conditions. Improving the accuracy of predictions, validating new methodologies (such as automated probes), and overcoming the scale limitations of methods including GHG chambers and animal respirometry are ongoing challenges. Furthermore, the use of remote sensing data must be refined and integrated with other information. Tackling these issues will require continuous investments in research and infrastructure. Overcoming these barriers is fundamental if Brazil is to effectively monitor its carbon stocks and GHG emissions on a large scale, supporting both national commitments and the needs of the productive sector for increasingly sustainable and competitive production. The aim is to have accessible, accurate, and reliable monitoring tools that support the climate goals of the country, the productive sector, and sustainable management of natural resources.

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From space to the field

An innovation to improve **soil management**

Improving soil management, increasing productivity at a lower cost, and simultaneously opening up new opportunities in the carbon market: this is the transformation made possible by a technology developed at Embrapa Instrumentation in São Carlos, São Paulo. This is LIBS, the abbreviation for laser-induced breakdown spectroscopy: an advanced, precise, and low-cost method adapted for rapid soil analysis. Used by NASA on missions to Mars to examine rocks and the planet's surface, this technology has gained unprecedented application in Brazilian agriculture. Embrapa has brought this robust, versatile, and internationally recognized tool "from space to the field," where it can revolutionize agricultural practices and pave the way for smarter and more sustainable agriculture.

This technique uses a high-energy laser pulse to vaporize a small portion of material (such as soil, plants, or rocks). This vapor forms a luminous plasma, whose light emissions are analyzed by a spectrometer. Each chemical element emits light at specific wavelengths, making it possible to identify and quantify the elements present in the sample.

This technology made the leap from the laboratory to the field in 2015 with the creation of Agrorobótica, a startup that emerged as a spin-off from Embrapa itself. Here science met entrepreneurship, and LIBS began to be applied in a practical way in everyday agriculture. Through a partnership based on an open innovation model, Embrapa and Agrorobótica have transformed LIBS into an intelligent and accessible tool: the AgLIBS AI platform, which incorporates artificial intelligence

to interpret laser data and convert it into precise agronomic recommendations.

With AgLIBS AI, farmers can now carry out soil analysis to determine nutrients, pH, cation exchange capacity, and also carbon content (which makes up around 50% of the soil's organic matter) in a faster, more accessible, and digital way. This reduces waste, improves management, and above all increases productivity with lower costs.

The impacts have reached far beyond the farm. This tool is being used in 17 Brazilian states and is already contributing to carbon credit projects, a new source of income for producers committed to sustainability. In 2023, the LIBS technique was internationally recognized by the Verra certification body in the United States as valid for measuring carbon in the soil — an important step towards credibility and certification for low-carbon agriculture programs.

AgLIBS AI is an example of how combining public research with private innovation can make a highly complex technology useful in the everyday lives of farmers. Today, this technique is present on rural properties in different biomes, in initiatives such as low-carbon soy, in contracts with large private companies linked to agribusiness, important cooperatives and rural producers' associations, and also in collaborations with universities and research centers.

This is an example of applied science, technological solutions with real impact, and increasingly intelligent and sustainable agriculture.





CHAPTER 5

The carbon balance of Brazil's main agricultural systems, protocols and representations

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Introduction

The carbon (C) balance in agricultural production systems (grain, fiber, bioenergy and livestock production systems) refers to the quantitative assessment of greenhouse gas (GHG) emissions, such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), compared to the capture and storage of C in plant biomass and soil. This concept is fundamental for understanding the climate impact of management practices and identifying ways to make these systems sustainable and resilient.

Agricultural and livestock production systems play an active role in the C cycle (Figure 5.1). In a natural environment, plants remove CO₂ from the atmosphere through photosynthesis, incorporating the C into organic molecules. This C can be returned to the atmosphere by the respiration of plants, animals and microorganisms, or it can be stored in the soil when the remains of plants and organic matter decompose.

In this way, production systems are continuously interacting with the environment and contributing to the increase or mitigation of global warming. They are influenced by the climate and other external factors. The resilience and adaptability of production systems (and, in turn, their sustainability) are directly impacted by climate change.

Agricultural sustainability therefore involves the search for production systems that maintain productivity without compromising natural resources. The C balance expresses the difference between the amount



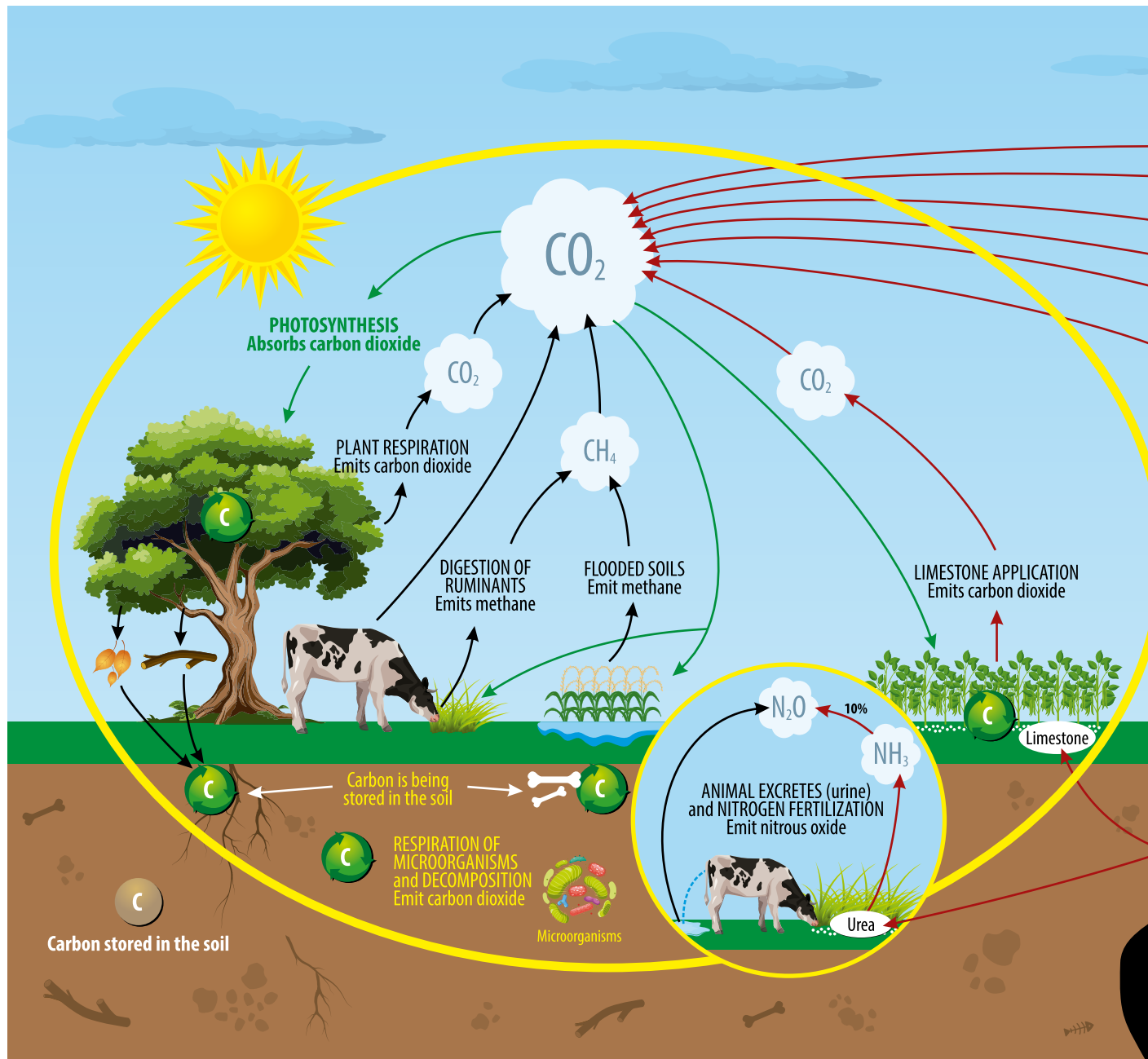
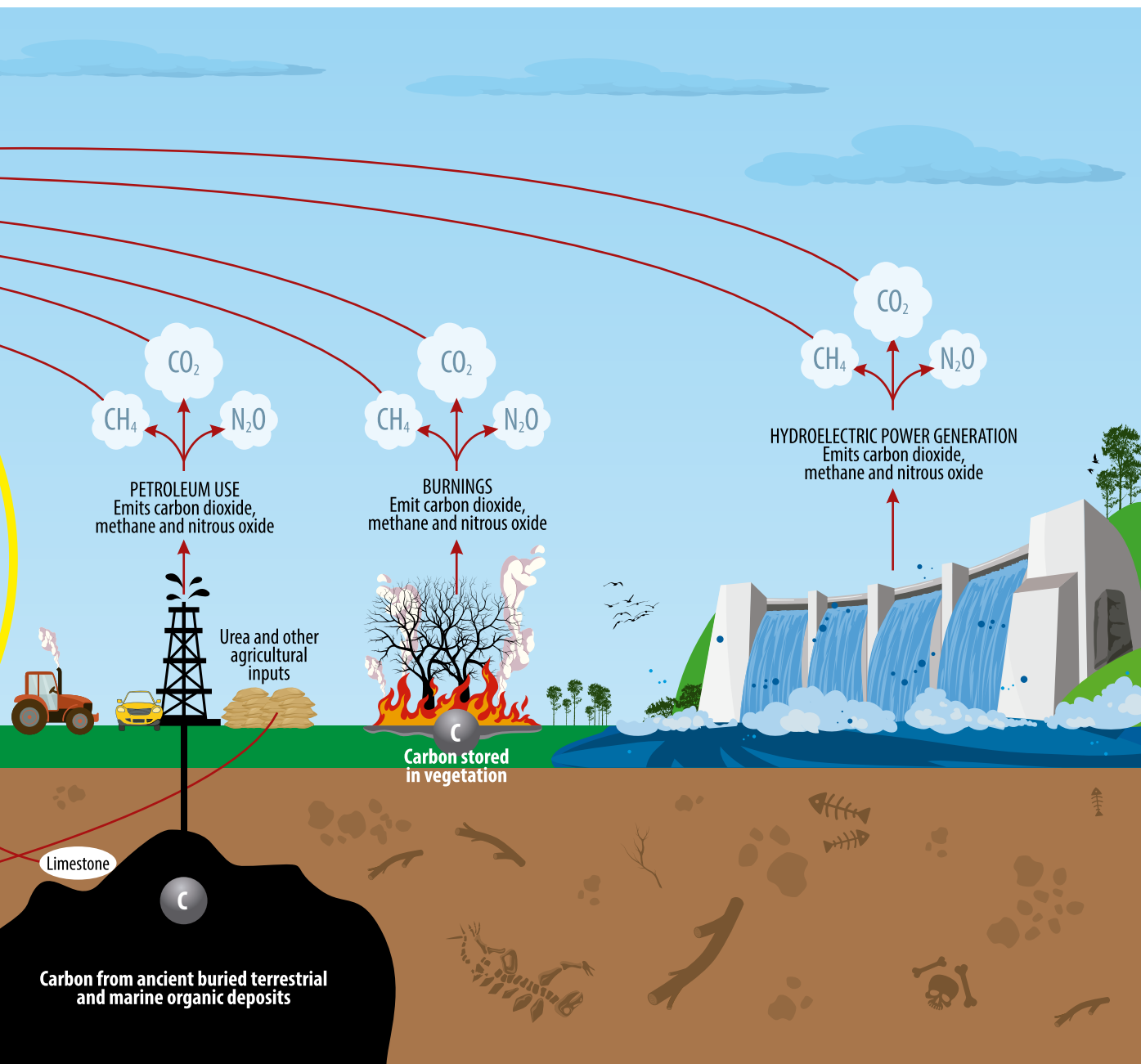


Figure 5.1. Agriculture in the carbon cycle. The green arrows represent the ways carbon is assimilated via photosynthesis, resulting in the accumulation of carbon in soil and vegetation. The black arrows indicate emissions pathways for greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), resulting from natural processes associated with agricultural and livestock activities that take place on rural properties (these include plant respiration, ruminant digestion, decomposition of organic matter in flooded soils, respiration of soil microorganisms, and excretion of animal urine and feces). The red arrows represent GHG emissions from the use of external inputs (such as urea and limestone) applied as part of farming activities, as well as in the production, mining, and transportation of these inputs off the farm (for instance, petroleum use, burning, and energy generation). The figure includes N_2O because although this gas does not contain carbon, it is accounted in carbon balance calculations as CO_2eq , considering that one molecule of N_2O has the same global warming potential as 273 molecules of CO_2 .



of C emitted and absorbed, making it possible to assess whether a system is contributing to climate change mitigation or exacerbating the problem. Production systems that emit large amounts of CO_2 , CH_4 , and N_2O without adequate compensation for C sequestration tend to be less sustainable, since they increase the concentration of GHGs in the atmosphere.

In contrast, adopting sustainable management practices can improve the C balance, by promoting the capture and storage of C in soil and vegetation. Technologies such as direct or no-till planting, crop diversification, and integrated production are efficient strategies for boosting the resilience and adaptive capacity in production systems and for mitigating GHG

emissions. These practices help maintain and improve soil quality, reducing demand for external inputs and using natural resources more efficiently.

In addition to positive environmental impacts, a favorable C balance also influences the economic viability of agricultural production. Producers who practice sustainable production can access financial incentives, such as payments for environmental services and participation in the C market, where producers can benefit from C credits or receive sustainability certifications for having adopted practices with low environmental impact.

Adopting strategies around balancing C strengthens food security and ensures that food is produced sustainably, minimizing climate risks that could compromise agriculture in the long term. In this way, the relationship between the C balance and agricultural sustainability is essential to ensure efficient, resilient production in line with global environmental needs.

The C balance is consequently a robust indicator of the suitability and sustainability of the farming model in use, and allows us to identify practices that balance productivity with environmental preservation.

Processes and mechanisms involved in carbon retention and emission

The dynamics of the C cycle in agriculture are more complex than in natural ecosystems, due to the wide variety of practices adopted in the production sector and their environmental impacts.

The biological processes of the soil, plants, production of inputs, and management of agricultural systems that result in GHG emissions are diverse:

Soil respiration and decomposition of organic matter: microbial activity in the soil releases CO₂, especially in intensive cultivation systems and areas with high mineralization of organic matter.

Ruminant digestion: enteric fermentation in cattle and other ruminants generates CH₄, one of the most potent GHGs.

Irrigated rice cultivation: the anaerobic decomposition of organic matter in flooded fields releases large quantities of CH₄.

Burning biomass: burning agricultural and forestry waste releases CO₂, CH₄, and N₂O.

Inadequate management of organic waste: storage and treatment of animal waste can result in the release of CH₄ and N₂O.

Use of nitrogen fertilizers: microbial transformation of nitrogen (N) in the soil can generate N₂O, a gas with high global warming potential.

Loss of N from agricultural systems via volatilized ammonia (NH₃): NH₃ is not a GHG, but can generate N₂O emissions if it is deposited into other areas, thus creating indirect emissions of this gas.

These sources of GHG emissions pose a major challenge. However, agriculture also offers opportunities for sequestering C, which can occur in various ways. The main natural process for removing C from the atmosphere is photosynthesis, where plants use energy from sunlight, water, and CO₂ to synthesize their above-ground biomass and roots and release oxygen (O₂) into the atmosphere. The process of photosynthesis complements autotrophic respiration, a predominantly nocturnal process by which plants release CO₂ into the atmosphere. In an ecosystem that is in equilibrium, the processes of photosynthesis and autotrophic respiration tend to be balanced: in other words, the ecosystem neither emits nor sequesters C in excess. In a system with a strong accumulation

of biomass, the process of photosynthesis prevails, and the ecosystem removes more CO₂ from the atmosphere than it emits. When this is combined with conservation soil management that prevents loss of CO₂ and other GHGs, it can result in an ecosystem that serves as a C sink. Planting trees in agricultural areas, for example, can store C in the biomass and in the soil. In well-managed pastures, leaf and root growth is stimulated, resulting in greater production of plant biomass. Through transformation processes in the soil, plant material from roots and plant biomass is incorporated into the soil and decomposed by the activity of fauna and microbiota, where it is converted into soil organic matter. Between 50 and 58% of soil organic matter is composed of C. Organic matter (another name for the C present in the soil) can be transformed into stable forms of C, which remain in the soil for long periods of time due to their chemical structure or physical protection by the soil structure. These stable forms contribute to C accumulation, which not only enables C sequestration in the production system but also improves the fertility and physical and biological properties of the soil, and is therefore essential for soil health.

Metrics for the carbon balance

The C balance is the difference between total GHG emissions and the amount of C sequestered in a production system. It is expressed in units as CO₂ equivalent (CO₂eq), which convert the impact of different GHGs in agriculture, typically CO₂, N₂O, and CH₄, into a common metric based on the global warming potential of each gas. According to the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (UN) (Intergovernmental Panel on Climate Change, 2022a), the global warming potential (GWP) of the main GHGs varies according to the time horizon considered. For a period of 100 years, the values are:

- Methane (CH₄): approximately 27 to 29 times the warming potential of CO₂.
- Nitrous oxide (N₂O): around 273 times the warming potential of CO₂.

These values reflect the capacity of these gases to retain heat in the atmosphere, significantly contributing to global warming.

The C balance can be described with a simple equation:

$$C \text{ balance} = C \text{ sequestration in the agricultural system} - \text{total GHG emissions from the agricultural system}$$

where *C sequestration* and *total GHG emissions* are expressed in CO₂ equivalent (CO₂eq).

In this way, a positive, more favorable balance indicates that the system is removing more C (CO₂eq) from the atmosphere than it is emitting. However, a negative balance, where emissions exceed removals, suggests that the system is contributing to global warming.

The C balance can be calculated for different scopes of agricultural production. It can be determined for a plot of land, a farm, the production chain of a product, a company or even an entire economic sector, among other approaches.

Metrics for determining the C balance in agricultural production are essential tools for assessing C emissions and sequestration in production systems. These metrics help to identify more sustainable practices and monitor the environmental impact of farming. The main metrics used are:

GHG emissions: measures the amount of CO₂, CH₄, and N₂O emitted by agricultural activities, such as enteric fermentation in livestock, fertilizer use, waste management and soil use and management.

C sequestration in the soil: evaluates the soil's capacity to store organic C, taking into account practices such as no-till or direct planting, crop rotation, recovery of degraded areas, and pasture management.

Net carbon balance: calculates the difference between total GHG emissions and sequestered C, providing an overview of the environmental impact of the production system.

Resource-use efficiency: analyzes the relationship between agricultural production and C emissions, promoting practices that maximize productivity with less environmental impact. For example, the amount of corn produced per kilogram of nitrogen fertilizer used.

Carbon footprint: expresses the total C emissions associated with the production chain of a given agricultural product, from production to final consumption.

Models and inventories: tools such as the System for Estimating Greenhouse Gas Emissions (SEEG) and IPCC protocols are widely used to standardize and compare C emissions and sequestration data.

These metrics are fundamental for guiding public policies, C markets, and sustainable practices in agriculture.

Determining the C balance in agricultural production requires fundamental basic data on the components that comprise the balance, such as GHG flows and the C content in the different compartments of the production system and the production chain. Direct measurements are very important and must be carried out with scientific rigor, because the results that are obtained will be used to determine and calculate factors, indices, and rates that feed databases and repositories with continuously updated information. This data, in turn, is used to feed specific models and protocols adapted to tropical

conditions and the needs of Brazil, depending on the metric used and the scope of the assessment.

In the context of international negotiations, it is essential to develop metrics and indicators, C balance models, and monitoring systems that allow the country to achieve a level of representation that is appropriate to the national reality.

The IPCC methodology refers to different levels (tiers) of complexity and precision in estimating GHG emissions. They are classified into three main levels:

Tier 1: the simplest method, based on global average emission factors and general activity data. It is used when more detailed information is not available.

Tier 2: uses emission factors specific to each country or region, providing greater precision in estimates.

Tier 3: a more detailed method, based on direct measurements, complex models, or specific inventories of emission sources.

The aim is to reach at least Tier 2, which uses specific national data, or preferably Tier 3, which uses models that were developed or parameterized, calibrated, and validated for the relevant soil and climate conditions and production systems in the country. Reaching this level depends on appropriate methods and protocols for collecting data and representing C stocks, emissions, and removals in Brazilian production systems. These methods and protocols must be internationally recognized and appropriate in order to represent the contribution of the national agricultural sector, including removals, the effects of good practices, and the characteristics of production models in a tropical environment.

Providing these measurements in a continuous and consistent manner requires investment in the instrumental and analytical infrastructure of

the network for obtaining field and laboratory data and information, as well as continuous adjustments to laboratory analysis methods, protocols, and infrastructure, and incorporating specialized researchers and collaborators to the team.

Current overview of greenhouse gas emissions from Brazilian agriculture and mitigation technologies

The conversion of natural areas for agricultural or livestock use is one factor that still contributes to unfavorable assessments of the C balance (C footprint) for production chains in Brazil. Deforestation, especially in tropical regions, releases large amounts of C stored in trees and soils and exacerbates the climate impact. Moreover, agricultural practices and biogeochemical processes can increase C loss and GHG emissions.

Enteric fermentation in ruminants generates large quantities of CH₄, a very potent GHG. Despite advances in the formulation of diets and additives that reduce these emissions, many producers still face challenges implementing these solutions due to cost and lack of information. Furthermore, practices such as waste management for biogas production are still not widely adopted, despite their potential to generate renewable energy and reduce environmental impacts.

Intensive use of chemical inputs (such as dependence on nitrogen fertilizers and pesticides) is one of the main challenges for reducing GHG emissions in agriculture. Synthetic fertilizers contribute to emissions of N₂O, a gas with significant global warming potential.

Reducing the use of these products requires sustainable alternatives, such as the use of organic fertilizers, crop rotation, use of bioinputs, and increased circularity on the farm.

Improper soil management can result in the release of stored C, reducing soil fertility and increasing GHG emissions. Practices such as plowing and harrowing and lack of permanent soil surface cover contribute to the degradation of soil organic matter. Techniques like direct planting (also known as no-till, combined with the use of cover crops and/or green manures and other sustainable practices, such as contour lines) and remediation of degraded areas help maintain C in the soil, but require technical training and economic incentives for large-scale adoption to take place.

Although there are technologies and agricultural practices that reduce emissions and increase C sequestration, such as integrated crop-livestock-forestry systems (ICLF), implementation in many cases still requires high initial costs, along with planning, investment, and changes in production. Producers may face difficulties obtaining credit and financing to invest in sustainable systems. Access to government incentives and C markets can stimulate the adoption of good practices, but challenges still remain in regulating and valuing these mechanisms.

The lack of infrastructure and limited access to new technologies, for example those promoted by the ABC+ Plan (Brasil, 2021) described below, make it difficult to implement low C emission strategies, especially on small farms.

Brazil has historically been a protagonist in international discussions on sustainable development since the UN Conference on Environment and Development (Rio 92, also known as the Earth Summit), and was the first of the 150 signatory countries to sign the United Nations Framework Convention on Climate

Change (UNFCCC), recognizing that the effects of climate change represent a concern shared by all of humanity. In 2009, Brazil's commitment was strengthened with the establishment of the National Policy on Climate Change (PNMC) via Law 12.187/2009 (Brasil, 2009). That same year, during the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 15) in Copenhagen, Brazil voluntarily presented the goal of reducing projected GHG emissions by between 36.1 and 38.9% by 2020. To achieve this target, the country proposed voluntary action programs that included an 80% reduction in the average annual rate of deforestation in the Amazon and a 40% reduction in the Cerrado biome. Brazil later reaffirmed and expanded its climate commitments by joining the Paris Agreement in 2015 during COP 21, ratified internally by Decree 9.073/2017 (Brasil, 2017). As part of this agreement, the country presented its Nationally Determined Contribution (NDC), setting a target to reduce its emissions by 37% compared to 2005 levels by 2025, and 43% by 2030 (Brasil, 2024a).

This was the context in which the first phase of the Plano Setorial de Mitigação e Adaptação à Mudança do Clima para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura – Plano ABC 2010–2020 (Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low Carbon Economy in Agriculture, known as the ABC Plan 2010-2020) was drafted (Brasil, 2012a), a strategic and pioneering initiative to reconcile food security with environmental sustainability through the adoption of low C emission technologies in land use and management. Over these 10 years, the ABC Plan fostered a portfolio of technologies with solid technical and scientific underpinnings which also taken into account economic, environmental, and social aspects, with adoption over a total of 54.03 million

hectares across the country, equivalent to 193.67 million Mg CO₂eq avoided (Brasil, 2023a).

The impact of this public policy motivated the Brazilian government to launch the Plano Setorial para Adaptação à Mudança do Clima e Baixa Emissão de Carbono na Agropecuária, com vistas ao Desenvolvimento Sustentável 2020–2030 (Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture with a view to Sustainable Development 2020-2030, also known as the ABC+ Plan) in 2021 (Brasil, 2021), as an expanded continuation of its sectoral policy for tackling climate change in the agricultural sector. The plan's general objective is to promote adaptation to climate change and control of GHG emissions in Brazilian agriculture and boost the efficiency and resilience of production systems, considering integrated landscape management.

In addition to the sustainable production systems (SPS_{ABC}) defined in the previous plan (which included recovery of degraded pastures, integrated crop-livestock-forest systems, also known as ICLF, agroforestry systems, direct planting, biological nitrogen fixation, and planted forests), three new SPS_{ABC} were incorporated into this new phase: direct planting for vegetables, irrigated systems, and intensive finishing for livestock. At this stage, agroforestry and ICLF systems were addressed separately, but within the same group known as Integration Systems. The scope of three other SPS_{ABC} was also expanded:

- Practices for recovery of degraded pastures now considers the recovery and renovation of pastures with some degree of degradation.
- Bioinputs includes biological nitrogen fixation and plant growth promoting microorganisms.
- Management of animal production waste now considers waste other than animal waste and encourages the use of byproducts as bioenergy and biofertilizer.

In this new cycle of the plan, the planted forests SPS_{ABC} also stands out, highlighting its significant potential to contribute to reducing GHG emissions, promoting C sequestration, and fostering sustainable forest-based production chains.

The planned targets are to expand the area where SPS_{ABC} are adopted by 72.68 million hectares, increase the treatment of animal waste by 208.40 million m³, and encourage the use of bioinputs and plants to improve efficient use of water and nutrients by agricultural crops, with an estimated mitigation capacity equivalent to 1,042.41 million Mg CO₂eq.

Furthermore, the ABC+ Plan has defined new objectives which simultaneously establish a set of challenges in the technical, scientific, and public management areas over the next decade:

- **Maintain** incentives to adopt and maintain conservationist and sustainable agricultural production systems, with increases in productivity and income, resilience, and control of GHG emissions.
- **Strengthen** actions to transfer and disseminate technologies, training, and technical assistance.
- **Stimulate** and **support** applied research to develop or improve sustainable production systems, practices, products, and processes, with a focus on increasing resilience, productivity and income, and controlling GHG emissions.
- **Create** and **strengthen** mechanisms to recognize and value producers who adopt sustainable production systems, practices, products, and processes.
- **Encourage, expand, and diversify** economic, financial, and fiscal sources and instruments linked to sustainable production systems, practices, products, and processes.

- **Improve** the ABC+ information management system to carry out monitoring, reporting, and verification (MRV) and to monitor and evaluate its portfolio of actions and results.
- **Foster** integration of agriculture into the landscape, in order to encourage environmental regularization of rural properties and sustainable production in areas of agricultural use (Brasil, 2020).

Innovative technological solutions for improving the carbon balance in Brazilian agriculture

Research and innovation are indispensable for sustainability in the agricultural sector. They drive the development of new technologies that boost the productivity and efficiency of crops and production systems. At the same time, they permit more rational use of natural resources, and result in solutions that strengthen the resilience of agricultural systems in the face of extreme events, guaranteeing food security as well as the stability and resilience of production chains. These factors are essential for maintaining competitiveness in the global market, where standards for quality and sustainability are increasingly demanding.

Investment in research and development fosters the integration of modern technologies and tools, which help to make more precise decisions, reduce operating costs, and optimize production processes. This modernization increases the profitability of producers and attracts investment, creating jobs and boosting the agricultural sector as a whole.

The culture of innovation encourages collaboration between universities, research centers, companies, and farmers.

This partnership, in turn, strengthens credibility and extends the reach of results and dissemination of the solutions developed to different audiences, from public policy makers to the private sector. Cooperation allows scientific and technical knowledge to be quickly transformed into practices that can be replicated on a large scale, increasing competitive gains and preparing the sector for the challenges of the future.

In short, research and innovation are the keys to sustainable, resilient, and competitive agriculture in the long term, ensuring a balance between production, environmental preservation, and economic progress.

Solutions to enable research and innovation aimed at improving the carbon balance of agricultural systems

The solutions that Embrapa is developing to enable innovation include its own databases and specific functionalities for the C balance in tropical agricultural systems, which are fundamental for the development of metrics platforms. To this end, it is essential to invest in updating, modernizing, expanding, and organizing scientific research infrastructure and data and information storage, as well as to develop advanced equipment and techniques for field data collection and modeling (the subjects of Chapters 3 and 4 of this book).

In order to adopt methods and parameters compatible with international standards that ensure transparency and precision in the measurement of C emissions and removals, Embrapa has developed specific protocols for sampling and determining GHG, C, and N flows in soil and biomass which are applicable to grain, livestock, and forestry production systems. These protocols are available in Embrapa's collection of publications (Higa et al., 2014; Oliveira, 2014a, 2014b; Urquiaga et al., 2016; Alves et al., 2017).

In this chapter, we highlight two other more recent solutions that are directly associated with providing quality data and information to develop sustainable production systems and monitor production systems at national and local levels.

Quality control for soil laboratories and proficiency test for soil carbon analysis – analytical quality and harmonization in soil analysis

For Brazilian agriculture to remain productive and environmentally sustainable, it is essential that the results of soil analyses carried out in specialized laboratories be correct and reliable. Soil analysis is the first step in checking whether there are enough nutrients for good plant growth and productivity. This information can be used to make more precise decisions about the right amount of lime and fertilizer to apply, supplying only the nutrients that are deficient and avoiding excesses.

Embrapa created the Program for Certification of Soil Laboratories (PAQLF) and the Proficiency Test for Soil Carbon Analysis (EPCS).

PAQLF is a program that began in 1992 and is coordinated by Embrapa Soils; its main purpose is to ensure that the results of soil fertility analyses are reliable. To do so, this program monitors whether laboratories carry out analysis of soil correctly and consistently. Today, 176 laboratories throughout Brazil participate in this program, and around 70% demonstrate that they carry out good quality fertility analyses every year. This quality control assessment verifies the quantity of the main nutrients, hazardous substances, and other important elements, as well as physical soil properties (such as sand, clay, and silt content). PAQLF is like a quality standard that helps laboratories to improve, and serves as an example for other programs, such as EPCS described below.

Many factors can influence the quality of soil analysis to assess soil fertility. Variation in results can lead to errors, compromising confidence in laboratories and in fertilizer and liming recommendations, which can cause losses for farmers and have negative impacts on Brazilian agriculture. If soil analyses show more nutrients than there actually are, farmers may use insufficient amounts of fertilizer and lime, which will harm production. However, if the tests show that there are fewer nutrients than the real value, excessive quantities of these inputs may be applied, generating unnecessary expenses and increasing the risk of environmental pollution, especially in bodies of water. In this way, increased reliability of the analyses leads to more precise recommendations for soil nutrient management, generating benefits for agriculture, the environment, and the economy.

The PAQLF program holds regular meetings with participating laboratories to encourage correct use of Embrapa's recommended methods and best laboratory practices. Because this is a nationwide and widespread program, farmers themselves only seek out laboratories that participate in and pass the proficiency test. This expectation encourages new laboratories to join the program, which accelerates improvement of their analytical quality and recognition of this quality in the market.

The proficiency Test for Soil Carbon Analysis (EPCS) is a more recent initiative, established in 2023 under the coordination of Embrapa Environment. This is the world's first interlaboratory program focused on soil C analysis. The main objective of this testing is to harmonize the results of soil C analyses between the participating laboratories, and foster a network of collaboration among them. EPCS takes into account both the scientific aspects related to proper quantification of C in the soil and growing demand for these analyses in the agricultural C market.

Adoption of internationally recognized methods is an essential aspect of soil C analysis. The most accurate, recognized, and reliable method for determining C in soil is the dry combustion technique, also known as the Dumas method. It uses equipment known as an elemental analyzer, which heats the soil sample to around 1,000 °C. At this high temperature, all the C in the sample is released and measured more precisely. Despite its high accuracy, this method is still not very common in commercial soil analysis laboratories in Brazil, mainly due to the high cost of purchasing and maintaining the equipment and the need for specific sample preparation.

Most laboratories analyze soil C using a cheaper but less accurate method called wet oxidation or the Walkley-Black method, which yields results that are often expressed as organic matter in the reports that reach the farmer. Although this method is more affordable, it is less accurate than dry combustion (the Dumas method) and generates hazardous waste such as chromium. Recognizing the limitations of this most common method, EPCS offers a crucial service: comparison of Walkley-Black results with the Dumas standard, and assessment of correct application of the reference method by laboratories.

The proficiency test also covers other innovative methods for determining C, which are presented as efficient alternatives to the Walkley-Black and Dumas methods. These new methods, detailed in Chapter 4, offer greater analysis capacity and lower costs, while maintaining the accuracy required to identify variations in soil C content. They use spectroscopic techniques, calibrated and modeled after the reference method, such as laser induced plasma spectroscopy (LIBS) and near infrared spectroscopy (NIR). The goal is for both the reference method and these alternatives to be adopted by commercial soil analysis laboratories, thus meeting not only the basic demand for C or organic matter analysis for

fertility management, but also the requirements of projects to generate C credits in agriculture.

Each year, between 28 and 38 laboratories have participated in the EPCS program. Of these, 60% to 70% use the Dumas method to measure C in the soil, while 30% to 40% use other techniques such as spectroscopy. Overall, the participating laboratories provide very accurate results. During the first year of testing 82% of the laboratories were deemed adequate, but this figure dropped to 62% in the second year. This difference occurred because preparation of the soil sample became part of the assessment from the second year onwards, since it is essential for correctly representing C content. It is common for laboratory performance to decline when a quality test introduces novelties; the flaws are then identified and corrected, leading to overall improvement in the quality of the results for clients.

In short, proficiency testing for soil analysis coordinated by Embrapa functions as a third party that lends credibility to the information generation system, preventing risks associated with inaccurate data, which can be harmful to farmers and the environment. The quality of analysis can have even more complex impacts, considering that communication and dissemination of information based on laboratory results is used in product negotiation and marketing systems, environmental certification programs, and public policies aimed at low C emissions or C sequestration.

Network of long-term field experiments and monitoring sites

The components of the C balance in agricultural systems, such as C stored in the soil, biomass, or GHG emissions, are regulated by dynamic biophysical processes that affect the compartments in the short, medium, and long terms. When investigating the C balance in agricultural systems, it is essential to use

well-documented long-term field experiments and monitoring sites (LTE). These experiments are living laboratories, providing data and information for the development of platforms and models for metrics adapted to Brazil's natural ecosystems and agricultural production systems. Data from LTE can be used to understand how specific management practices like the cropping system or fertilizer application contribute to increased C storage and sequestration in the soil, or to GHG emissions under different environmental conditions (soil, climate, ecosystem). For this reason, LTE sites and studies are very well suited experimental models for generating and providing scientific knowledge on agronomic practices that are relevant to the sustainability and stability of production systems (Schillinger, 2011). They make it possible to understand future changes based on trends observed in the past, thus offering a scope for the use of modeling and simulation work. Long-term monitoring is essential when considering the parameters characterized by slow temporal dynamics. When studying complex systems, short-term responses are like looking through a microscope, and may not reflect trends that manifest over decades. Short experiments of up to approximately ten years are able to focus only on the initial trajectory or fluctuations, while long-term experiments allow us to describe the mechanisms involved in the temporal dynamics and variation of trajectories over time (Knapp et al., 2012). They are also essential for evaluating and predicting the impact of adopting soil management practices on soil quality and health, as well as for studying the evolution of crop yields, for instance, in addition to promoting the integration of studies that involve biological, biogeochemical, environmental, and economic dimensions.

Embrapa has consequently invested a great deal of effort not only in maintaining long-term experiments, but also in forming a network of long-term experiments, which involves the

significant challenge of organizing the resulting historical data into a secure repository to ensure it can be made available for future studies. Under Embrapa's leadership, the International C-arouNd Consortium (Figure 5.2) was recently established, bringing together 40 long-term experiments around the world, 17 coordinated by Embrapa units. This network foresees the continuous incorporation of experiments and new initiatives, according to the needs of scientific progress.

In order to ensure the consistency and comparability of databases over time and permit synthesis of this knowledge, the International C-arouNd Consortium promotes the cataloging of standardized data and metadata. Data from LTE overseen by Brazilian collaborators is stored in Embrapa's REDAPE research data repository, while data from international partners is recorded in the Zenodo repository. Both utilize the same security and traceability principles. REDAPE is an institutional platform created by Embrapa to store, preserve, and provide agricultural research data. This repository strives to promote transparency, accessibility and, above all, reuse of the scientific data generated by Embrapa and its partners, ensuring that this data is available

for the scientific community, farmers, and other interested parties. Filling in the metadata fields in a standardized manner makes it possible to extract and cross-reference data based on relevant elements for classification, such as soil or climate type. It is also possible to retrieve data according to the year the experiment began, land use, treatments, and geographic coverage. This approach strengthens the knowledge base on changes in soil processes over time and fosters global collaboration in research, increasing possibilities for other researchers to use the data. Standardized data, combined with modeling tools and artificial intelligence, have immense potential for sustainable soil management and production systems in general, contributing to more effective solutions to environmental challenges.

Solutions to control greenhouse gas emissions and increase carbon sequestration in agricultural and forestry production systems

This section presents some of the technologies of the ABC and ABC+ Plans described in the current

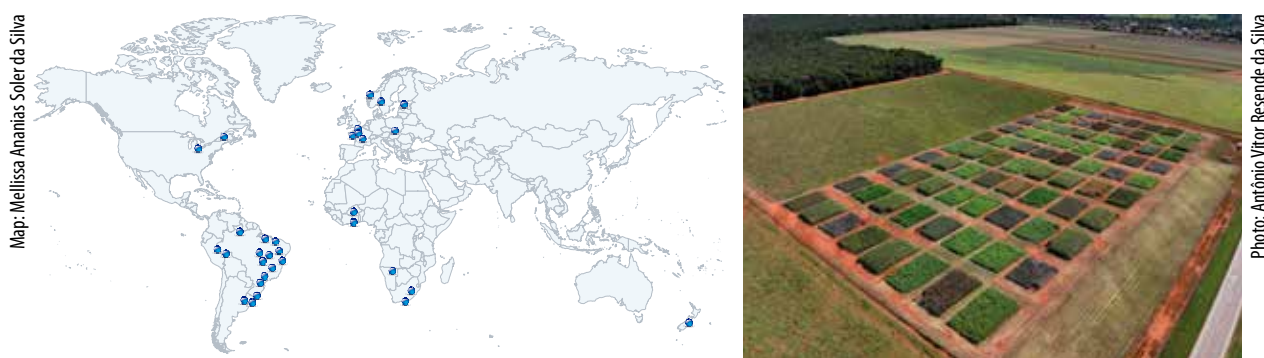


Figure 5.2. Locations of the International C-arouNd Consortium's long-term experiments (left). Long-term experiment that is part of the C-arouNd International Consortium, involving a direct planting (no-till) system with rotation, succession, or consortium schemes for various agricultural crops, cover crops, and green manures, focusing on the main crops of cotton, soybeans, corn, and common beans (right). This experiment has been conducted since 2014 in clayey latosols by Embrapa Rice & Beans at the Capivara Farm, in Santo Antônio de Goiás, Goiás (Projeto Sistemas integrados de produção de grãos e fibra para mitigação dos efeitos da seca [Project: Integrated grain and fiber production systems to mitigate the effects of drought], Embrapa SEG 20.18.03.026).

overview section as solutions, with significant contributions from Embrapa in collaboration with its various partners. It begins with solutions that are nationally relevant in general, and ends by highlighting technologies of local or regional importance.

Recovery of degraded pastures

Brazilian livestock production is mostly based on pastoral systems involving zebu genetics and tropical pastures, and some niches (such as the Pampas biome) with taurine genetics and temperate pastures. These climatic adaptations have made it possible to use pasture in all of Brazil's soil and climate conditions. Only 6.96 million head, corresponding to 16.58% of the total herd (ABIEC, 2024), passed through feedlots during the final fattening phase. Breeding and rearing are carried out almost exclusively on pasture (Oliveira; Oliveira, 2024).

Pasture degradation results from the adoption of extractive livestock farming with low production rates and no concern for perennialization, namely preservation and continuous renewal of the pasture and natural resources (Oliveira; Corsi, 2005). In general, absence of physiological management for forage plants and soil fertility correction and maintenance contributes to pasture degradation (Oliveira; Corsi, 2005; Dias-Filho, 2011). Other important causes in Brazil, according to Dias-Filho (2011), are lack of periodic fertilization, failures in pasture establishment, and biotic problems like attacks by insect pests and, more recently, Marandu grass death syndrome in the Northern region.

A pasture can be considered degraded within a relatively wide range of conditions. The extremes of these conditions are conceptually considered agricultural degradation and biological degradation (Dias-Filho, 1998, 2011; Macedo, 1999). In agricultural degradation, there is an increase in the proportion of weeds in the pasture, which gradually reduces the

carrying capacity. In biological degradation, the soil loses its capacity to significantly sustain plant production, leading to the replacement of pasture with plants that demand little in terms of soil fertility, or areas devoid of vegetation that appear with bare soil (Dias-Filho, 2011).

In this sense, pasture recovery is very important and desirable for Brazilian livestock farming, which has favorable soil and climate conditions for livestock production in pastoral environments. Recovering a pasture consists of using the plant population and employing techniques that promote recovery, and can be carried out in various ways including direct pasture recovery, consortium planting with legumes, and incorporating various integrated crop-livestock systems proposed in the literature (Oliveira, 2007; Oliveira; Oliveira, 2024).

Pasture-based systems, when well managed in terms of animals and forage plants, are sustainable and offer the livestock sector many opportunities connected to animal welfare. Animals raised on pasture are in an environment that more closely resembles their natural habitat, which reduces stress, environmental pollution related to crowding, and excreta management, as well as the health problems typical of confinement. These systems also help tackle climate change, since well-managed pastures can sequester C and promote the land-saving effect, which reduces pressure for deforestation and favors preservation of biodiversity (Martha Junior et al., 2012; Segnini et al., 2019; Oliveira et al., 2020, 2021a, 2024a, 2024b). Intercropping grasses with legumes amplifies these benefits, especially in relation to the C balance, with emphasis on BNF (Matta et al., 2024), which favors C sequestration (Oliveira et al., 2024b) and reduction of enteric CH₄ emissions due to the presence of secondary compounds in legumes (Boddey et al., 2020; Furtado et al., 2023; Homem et al., 2024).

Many activities have made pasture-based livestock systems sustainable in Brazil. In 2023, the national cattle herd was estimated at 197 million head, distributed over a grazing area of 161 million hectares, which represents an 11.3% reduction in the area used over the last 20 years. During this period Brazil's average productivity nearly doubled, from 36.2 to 65.8 kilos of carcass per hectare. Under the logic of sustainable intensification, Brazil has increased its productivity to produce more in a smaller area (ABIEC, 2024). Furthermore, the Programa Nacional de Conversão de Pastagens Degradadas em Sistemas de Produção Agropecuários e Florestais Sustentáveis (National Program for Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems) (Brasil, 2023b) was also established; among various practices, it recommends intensification of beef cattle farming, which includes pasture recovery.

All these actions involving the recovery and intensification of Brazilian pastures (which cover an area of more than 160 million hectares) can contribute to mitigating GHG emissions and helping to control climate change, a phenomenon that is not restricted to national borders and affects the world as a whole.

Integrated crop-livestock-forestry systems

Integrated systems offer an efficient and relatively more sustainable way of producing food, fiber, and wood or biomass energy. Instead of allocating areas exclusively for agriculture, livestock, or forestry separately, this system combines the three activities in the same space in such a way that promotes a natural balance between them. They can be structured in different ways, depending on climatic conditions, soil type, and the productive objectives of the property (Oliveira et al., 2018). In terms of climate, in the regions of southern Brazil with colder

winters, black oats and rye grass are commonly used for grazing beef or dairy cattle, and after they dry out serve as mulch for no-till planting of soybeans or corn in the summer. Sandy soils tend to lose organic matter more quickly than clayey soils. For this reason, an integrated crop-livestock system that involves a two-year brachiaria grass pasture phase followed by one year of grain cultivation can offer greater resilience to the different land uses than an ICLF system with a predominantly agricultural phase (Skorupa; Manzatto, 2019). The main modalities of ICLF systems, according to Balbino et al. (2011) are:

Crop-livestock or agropastoral integration

(CLI): a system that integrates crop and livestock components in rotation, consortium, or succession in the same area, during the same agricultural year or over multiple years.

Crop-forest or agroforestry integration

(CFI): a system that integrates forest and crop components through the intercropping of tree species with annual or perennial agricultural crops. The crop component can be used in the initial phase of implementing the forest component, or in cycles during the system's development.

Livestock-forest or silvopastoral integration

(LFI): a system that integrates the livestock and forest components in a consortium (Figure 5.3).

Integrated crop-livestock-forestry (ICLF):

a system that integrates crop, livestock, and forest components in rotation, consortium, or succession in the same area. The crop component is usually preferred at the beginning (approximately two years) so that the livestock does not damage the young trees, after which it can be used in cycles as the system develops.

Because they have similar characteristics (Almeida et al., 2013; Aragão et al., 2023), ICLF and agroforestry systems have received joint support from public policies, for example in the ABC+ Plan for the period 2020 to 2030 (Brasil,

2021), which includes both in the technology called Integration Systems.

Each form of integration seeks to optimize land use, promoting synergy between production activities. This synergy occurs when the components (for example, the crops, livestock, and tree component) and the abiotic elements interact in a complementary manner so that the available means of production can be used more efficiently (Balbino et al., 2011). An integrated production system is capable of boosting the resilience and, in turn, the sustainability of agricultural production by providing better conditions to cope with climatic variations, among other factors. The tree component, for example, provides shade, improves the microclimate for animals, and contributes to the formation of regional rainfall, improving crops. Livestock farming provides natural fertilizers through animal waste and favors greater soil cover due to the large amount of biomass, which enriches and protects the soil against erosion. The crop component, in turn, contributes to diversity, benefiting pollinators and promoting soil health. Integration systems are one of the main technological bases for sustainable as well as ecological intensification. These practices are

fundamental for preserving natural resources and the economic efficiency of the agricultural sector.

Integrated crop-livestock-forestry (ICLF) systems, especially those involving no-till planting with crop rotation, are among the most sophisticated synchronizations of land use and management, with highly efficient use of inputs, space, and time for production of food and energy while simultaneously maintaining other ecosystem services. The term ecosystem services refers to processes that ensure the balance and sustainability of the production system. They may involve environmental regulation, such as controlling temperature, humidity, and nutrient availability in the soil; ecological regulation, characterized by improved biodiversity, hydrological cycling, pollination, C accumulation, more efficient nutrient cycling, and by reducing the negative impacts of production, such as erosion and soil degradation; and productive regulation, which incorporates integrated management to optimize the performance of crops, livestock, and trees (Millennium Ecosystem Assessment, 2005; Herrero et al, 2012; Ferraz et al., 2019; Moura et al., 2023; Madari et al., 2024; Matos et al., 2025).

Photos: Beata Enolke Madari



Figure 5.3. Degraded pasture (left) and crop-livestock-forestry integration (ICLF) (right) with the forest species *Schizolobium* sp. at the Gamada Farm in Nova Canaã do Norte, Mato Grosso. The forest species in this integrated system is *Schizolobium* sp.

Note: Projeto Carbioma: Agropecuária sustentável no Cerrado e na transição Cerrado-Amazônia (Project Carbioma: Sustainable agriculture in the Cerrado and the Cerrado-Amazon transition); Embrapa SEG 02.11.05.001 / CNPq 562601/2010-4.

From an economic point of view, diversification in the supply of products generated on the farm provides producers with alternatives to maximize profits by benefiting from natural price fluctuations in agricultural product markets (Reis et al., 2021).

Reis et al. (2023) used a mathematical model based on fuzzy logic to evaluate 22 rural properties in the three biomes in the state of Mato Grosso (Cerrado, Pantanal, and Amazon), considering economic, environmental and social sustainability metrics, and obtained revealing results. Farms that adopted crop-livestock integration (CLI) or livestock-forestry integration (LFI) had better sustainability indices than farms specializing in monoculture grains or continuous grazing. These integrated systems proved to be more balanced, making better use of natural resources and ensuring less environmental impact.

Although large farms containing an average of 2,648.5 hectares of continuous grain cultivation (especially soy and corn) adopted advanced technology and had the highest profit margins, averaging USD 607.03 per hectare, their production costs were higher, due to intense use of inputs such as fertilizers and pesticides. Meanwhile, properties dedicated exclusively to beef cattle, with an average size of 1,120 hectares, had low productivity and a high environmental impact, mainly due to GHG emissions (average of 1.95×10^8 tons $\text{CO}_2\text{eq J}^{-1}$) and low utilization of technology in animal management.

The major highlight of the study was the farms with crop-livestock integration systems (CLI). They achieved slightly higher grain yields than the monoculture farms and demonstrated negative values (average of -1.11×10^{11} tons $\text{CO}_2\text{eq J}^{-1}$) for GHG emissions, which means that they not only reduce pollution but can also capture C from the atmosphere. Furthermore, these farms stood out in terms of social issues,

since they had workers with more skills and a higher level of education.

A wide-ranging survey on the adoption of ICLF systems involving over 7,000 interviews conducted in Brazil between 2015 and 2016 found that the main motives that led farmers to adopt integration systems were reduced environmental impacts, the possibility of pasture recovery, and the advantages offered by crop rotation. Among grain producers, the most important factors for adopting ICLF were increased profitability per hectare and reduction in financial risks (Skorupa; Manzatto, 2019).

No-till or direct planting

The need to ensure greater productivity without expanding the agricultural frontier and to reduce the impact of agricultural production on the environment requires sustainable intensification strategies that optimize the use of inputs and cultivated areas (Garnett et al., 2013). Crop rotation has been shown effective in reducing risks and adapting to climate change (Ewing et al., 2024), promoting resilience and better use of natural resources. No-till farming associated with crop diversification strengthens the retention of C in the soil, improving its quality and reducing production losses, thus ensuring greater stability in agricultural income.

No-till planting (also known as direct planting) emerged in Brazil in the 1970s at the initiative of farmers, and expanded slowly over the following decades. But between 2006 and 2017 the area involving no-till soared by 84.9% to reach 33 million hectares (Fuentes-Llanillo et al., 2021) and, more recently, 41 million hectares.¹ This system is based on three principles: crop rotation,

¹ E-mail/telephone communication from Rafael Fuentes-Llanillo, researcher at the Instituto de Desenvolvimento Rural do Paraná (Paraná Rural Development Institute), sent to Alexandre Cunha de Barcellos Ferreira, researcher at Embrapa Cotton, on 22 Apr. 2025.

soil tillage restricted to the sowing line, and permanent soil cover using live plants and/or plant waste (mulch or stubble left after harvest). However, even decades after implementation of this system, no-till has been adopted in crops with insufficient soil cover, which compromises its protective effectiveness. This limitation is observed in the Cerrado, for example, in rotations where the main crop is soybeans followed by corn or cotton as a second crop; it can also be seen in the Southern region of the country, where there is a predominance of soybeans in the summer and fallow land in the winter. In the South, of the 17.5 million hectares sown with summer crops, only 3 million hectares are used for winter crops, most notably wheat and, to a lesser extent, oats, barley, triticale, and rye (IBGE, 2025). In the Cerrado of the Matopiba region, high temperatures combine with low-clay soils to accelerate decomposition of organic matter, significantly complicating accumulation of mulch and soil cover.

No-till planting, which integrates practices associated with rational management of soil, water and inputs, has become one of the pillars of sustainable agriculture in Brazil (Sá et al., 2025). The benefits of no-till in Brazil's tropical and subtropical environments include improved soil and water conservation, increased soil C stocks, reduced GHG emissions, greater water retention capacity, mitigation of the effects of drought and rising temperatures, production stability, breaking the cycle of insect pests and diseases, weed control, cost reduction, better use of inputs, climate resilience, and consequently, increasing or maintaining high levels of crop productivity. Moreover, no-till planting can help meet the environmental requirements of international markets that center around cleaner production

and the C market, along with adoption of regenerative agriculture practices (Figure 5.4).²

Although the C market in Brazil is still in its infancy and only operates within the scope of the voluntary market, and the advantages of no-till in reducing GHG emissions may reflect directly in economic benefits to the farmer, no-till planting is directly integrated into public policies and climate goals. It also contributes to greater production security and stability, and improves the adaptive capacity of agricultural systems, generating positive effects for the national economy. Within this context, the farmer's role in promoting sustainability is associated with the adoption of conservation agriculture, where soil and crop management is centered on no-till systems.

Adopting no-till planting is strategic for tackling challenges such as soil degradation, water insecurity, climate variability, and growing demand for food. Its environmental benefits include reducing erosion, boosting water infiltration into the soil, sequestering C, and improving soil biodiversity. From an economic point of view, highlights include increased productivity with less use of inputs, the land-saving effect, production stability, and climate resilience. The social benefits are related to food security, income generation in the countryside, and valuing farmers.

² The photo of the bean plant is part of the Integra C project: Tecnologia para sequestro de C em sistemas integrados de produção agropecuária no Cerrado (Integra C: Technology for C sequestration in integrated agricultural production systems in the Cerrado) (Embrapa SEG 20.18.03.043). The photo of the cotton plant is part of the project entitled Sucessão e rotação de culturas: superação de desafios e aperfeiçoamento do processo produtivo do algodoeiro no sistema plantio direto (Crop succession and rotation: overcoming challenges and improving cotton production in the no-till system) (Embrapa SEG 02.12.08.003).



Photo: Beata Esmak Madari



Photo: Alexandre Cunha de Barcellos Ferreira

Figure 5.4. Common beans (*Phaseolus vulgaris* BRS FC104) planted in brachiaria grass straw (*Urochloa brizantha* BRS Paiaguás) as part of a crop-livestock integration system, with co-inoculation of seeds with *Rhizobio tropici*, *freirei* and *leucaneae* for BNF, as well as foliar application of *Azospirillum brasiliense* to stimulate plant growth, at the Capivara Farm, Embrapa Rice & Beans, in Santo Antônio de Goiás, GO (left); cotton (*Gossypium hirsutum*) sown in brachiaria grass straw (*Urochloa ruziziensis*), in Santa Helena de Goiás, GO (right).

Planted forests (pine and eucalyptus)

Forests play an essential role in mitigating the effects of climate change and regulating the climate (Waring et al., 2020). They also provide a series of fundamental environmental services, such as water production, soil conservation, and improving air quality (Intergovernmental Panel on Climate Change, 2018). Preservation of planted forests minimizes GHG emissions associated with deforestation. Reforestation can remove between 40 and 100 billion tons of C from the atmosphere (FAO, 2025), which is equivalent to approximately a decade of anthropogenic emissions at current rates (Intergovernmental Panel on Climate Change, 2018). These environmental services help reduce exposure to climate risk, while strengthening adaptive capacity and national competitiveness in a scenario of greater environmental demands.

The biomass of planted forests contains approximately 47 to 50% C, and C stocks are directly linked to forest productivity, defined as the difference between production via photosynthesis and consumption from respiration and harvesting. Globally, it is estimated that these forests remove

around 5 to 6 billion tons of CO₂ from the atmosphere each year (Intergovernmental Panel on Climate Change, 2022b) and store 82 to 86% of the C present in the living biomass above ground (Six et al., 2002).

Finally, forest soils are fundamental in the C cycle, and are responsible for storing more than two-thirds of the organic C in global soil reserves (Ahmed, 2018), reinforcing their importance in mitigating environmental impacts and preserving biodiversity.

The C stocks in a forest ecosystem can be divided into three main compartments:

- Carbon present in the living biomass of trees: trunk, branches, leaves, and roots.
- Carbon present in dead biomass: necromass (in other words, dead biomass, which includes decaying trunks, branches, leaves, and roots) and leaf litter, the layer of organic matter made up of leaves, branches, fruit, and other plant residues that accumulate on the forest floor.
- Carbon contained in the organic matter in forest soil.

Most of the C in a forest is present in the living biomass (44%) and soil organic matter (45%). Smaller portions of C in the forest are present in the leaf litter, corresponding to 6%, and in dead wood, which represents 4% of the total stock (Grafton et al., 2021). These proportions and the amount of C stored in each compartment depend on climate, age, and forest management aspects such as spacing, thinning, pruning, fertilization, and weed control.

C sequestration in timber forest products also depends on the intended use of the harvested wood, since different uses determine the longevity of C storage and rate of GHG emissions. For example, use of wood in construction and furniture prolongs C sequestration for decades or even centuries, while paper and cellulose (as in packaging and cardboard) have a short cycle, since they are quickly discarded and decomposed or recycled. Use as an energy source (biomass) quickly releases the stored C, making this a short-term process similar to natural decomposition. Industrial and agricultural waste like sawdust, bark, and other byproducts can be used to produce wood panels, prolonging C storage of C; if they are disposed of improperly, they degrade rapidly and release C into the atmosphere.

Pine and eucalyptus are economically significant crops in the country, and account for over 90% of the planted forest area, which currently totals 10 million hectares. Considering the importance of these crops, the components of the C balance have been monitored in the main productive regions. For pine, monitoring took place in southern Brazil, while for eucalyptus the analysis covered a wider area, from Rio Grande do Sul to Pará, through projects coordinated by Embrapa. The inventories show that eucalyptus biomass in trees between six and seven years of age contains an average of 76 tons of C per hectare (Table 5.1). Similarly, planted pine trees near harvest age store around 145 tons, while the C stored in the soil in the 0 to 100 cm layer reaches approximately 190 tons of C per hectare (Table 5.2).

In Brazil, C stocks in pine plantations exceed 348 million tons, considering that the current cultivated area is approximately 1.8 million hectares (Indústria Brasileira de Árvores, 2024). In eucalyptus, on the other hand, stored C values vary more widely. A national survey conducted by Zanatta et al. (2020) identified an average stock of 42.2 tons of C per hectare in the 0–20 cm layer, with values ranging from 16 to 102 tons per hectare.

Table 5.1. Carbon stocks in the tree component of eucalyptus forests in Brazil by age group, expressed in tons per hectare.

Age (years)	State	C stock in aerial biomass	C stock in root biomass	Reference
		(t/ha C)		
Mean 2–3	MG, RS	15.7	5.6	Gatto et al. (2011), Wink et al. (2015) and Araujo et al. (2017)
Mean 4–5	MG, BA, SP	43.8	8.6	Stape et al. (2008), Gatto et al. (2011) and Rodrigues (2017)
Mean 6–7	SP, MG, BA, PR	63.1	13.3	Paixão et al. (2006), Stape et al. (2008), Gatto et al. (2011), Salvador (2015), Scarano and Ceotto (2015) and Souza (2019)
Mean 8–20	MG and RS	97.1	18.5	Gatto et al. (2011) and Wink et al. (2015)

Table 5.2. Carbon stocks in the tree component and in the forest soil of pine forests and native vegetation in Brazil, as a function of age, expressed in tons per hectare.

Age (years)	Soil class	Soil	Biomass ⁽¹⁾		Leaf litter	Reference
		0-100 cm	Aerial	Root		
		(t/ha C)				
5	Chernosols	227.8	15.3	3.6	7.7	Balbinot et al. (2003)
17	Chernosols	216.2	141.4	33.8	6.6	Veloso et al. (2018)
–	Chernosols	209.0	73.3	17.4	2.2	
18	Latosols	135.7	116.0	9.1	9.4	Ibarr et al. (2022)
–	Latosols	199.7	79.2	19.0	3.5	
21	Argisols				10.3	Kleinpaul et al. (2003)
16	Chernosols		73.3	25.4	13.2	Sixel et al. (2015)
17	Chernosols		121.7	16.2	7.0	Witschoreck (2008)
18	Cambisols		109.9			Sette Junior et al. (2006)
7	Latosols		63.4	17.1	4.7	Deliberali (2015)
16	Cambisols		58.0	6.8	8.6	Watzlawick (2003)
–	Cambisols		88.6	14.7	3.1	
25	Chernosols		185.2	37.6	14.1	Bizon (2005)
9	Haplic chernosols		53.6			Munhoz (2011)
Mean <10			44.1	10.4	6.2	
Mean >10			115.1	21.5	9.8	

Forest soils play an essential role in removing GHGs, serving not only to absorb CO₂ but also as drains for CH₄, a gas with 27 times greater global warming potential than CO₂ (Intergovernmental Panel on Climate Change, 2021). This capacity results from the activity of methanotrophic bacteria, which use CH₄ as a source of energy and C, making a significant contribution to mitigating emissions of this potent GHG. These bacteria are present in various environments such as forest and agricultural soils, and help reduce the concentration of CH₄ in the atmosphere. In pine and eucalyptus plantations, they promote an average influx of 3 to 5 kg of C in the form of CH₄ per hectare per year (Veloso et al., 2019; Oliveira et al., 2021a; Ibarr et al., 2022; Rodrigues

et al., 2023). Considering the vast area cultivated in Brazil with these species, and assuming a rate of 3 kg of C from CH₄ per hectare per year, it is estimated that forest soils can mitigate up to 1 million tons of CO₂eq annually, highlighting their importance in balancing the C cycle and reducing climate impacts.

Flows of N₂O in forest soils are relatively low, due to the reduced amount of nitrogen fertilizers applied to these crops. Doses are usually less than 100 kg N per hectare (Moreira et al., 2017), for a cycle of 7 years for eucalyptus and 15 years for pine.

Brazil can benefit significantly from the planted forest sector, since few countries have Brazil's

favorable climatic conditions and adequate technology for forest production. These advantages not only have provided the country the best productivity rates in the world (Indústria Brasileira de Árvores, 2024), but also allow the C balance in planted forest systems to be positive, making it possible to generate income through certification of forest products with low C emissions and sale of C credits. The importance of planted forests with a technology that has the potential to mitigate GHG emissions is recognized in the national plan for agricultural adaptation and mitigation, and represents 50% of the mitigation target from 2020 to 2030, mainly due to the increase in planted area (on the order of 4 million hectares).

Ecosystem restoration

Thirteen years ago, Brazil passed Law 12.651/2012 (Brasil, 2012b), known as the Native Vegetation Protection Law or, more commonly, the new Forest Code. This legislation establishes general guidelines for the protection of native vegetation, covering Áreas de Preservação Permanente (Permanent Preservation Areas, APPs), Reservas Legais (Legal Reserves, RLs), and Áreas de Uso Restrito (Restricted Use Areas, AURs). The law is part of a set of legal standards regulating land use and the conservation of natural resources in Brazil, complementing other legal instruments such as Law 6.938/1981 (Brasil, 1981), which establishes the National Environmental Policy, and Law 9.605/1998 (Brasil, 1998), known as the Environmental Crimes Law. Its main mechanisms include the establishment of the Rural Cadastro Ambiental (Rural Environmental Registry, CAR) and creation of the Programas de Regularização Ambiental (Environmental Regularization Programs, PRA) to be implemented by the states and the Federal District. More than a decade on, the majority of rural properties and holdings in the country have now been registered in the National Rural Environmental Registry System (SICAR), allowing the federal government and

state environmental agencies access to the location and environmental status of these areas. By evaluating and verifying the information provided, any environmental liabilities on rural properties and holdings in the country can be identified, namely degraded or altered areas.

The main protected areas in rural properties or holdings are APPs and RLs. APPs are areas that may or may not be covered by native vegetation, but contribute to the protection of soil, water resources, water supply (quantity and quality), fauna, and flora, along with other benefits. The main categories of APP include areas along bodies of water, surrounding springs, transitional *veredas* areas where the water table is close to the surface, lakes, and steeply sloping areas ($>45^\circ$). The size of APPs to be maintained or recovered, as well as the regime for their use, depend on various factors that are established in the legislation (Brasil, 2012b; Skorupa et al., 2024). Meanwhile, RLs are areas with native vegetation that must be maintained within a rural property or possession in order to ensure sustainable economic use of natural resources, protecting fauna and flora and helping to maintain or rehabilitate ecological processes. Their minimum dimensions depend on the geographical location of the property within the country, and are expressed in percentages of the area of the rural property or possession (Figure 5.5). Forms of recomposition or compensation and their use are also defined by law.

According to the Forest Code Thermometer platform (Observatório do Código Florestal, 2025), estimations based on SICAR data indicate that Brazil has environmental liabilities in rural property areas totaling around 16 million hectares in RLs and around 3 million hectares in APPs. In areas of settlements, these liabilities are estimated at around 1 million hectares of RLs and 135,000 hectares of APPs. An overview of the distribution of these liabilities is shown in Figure 5.6.

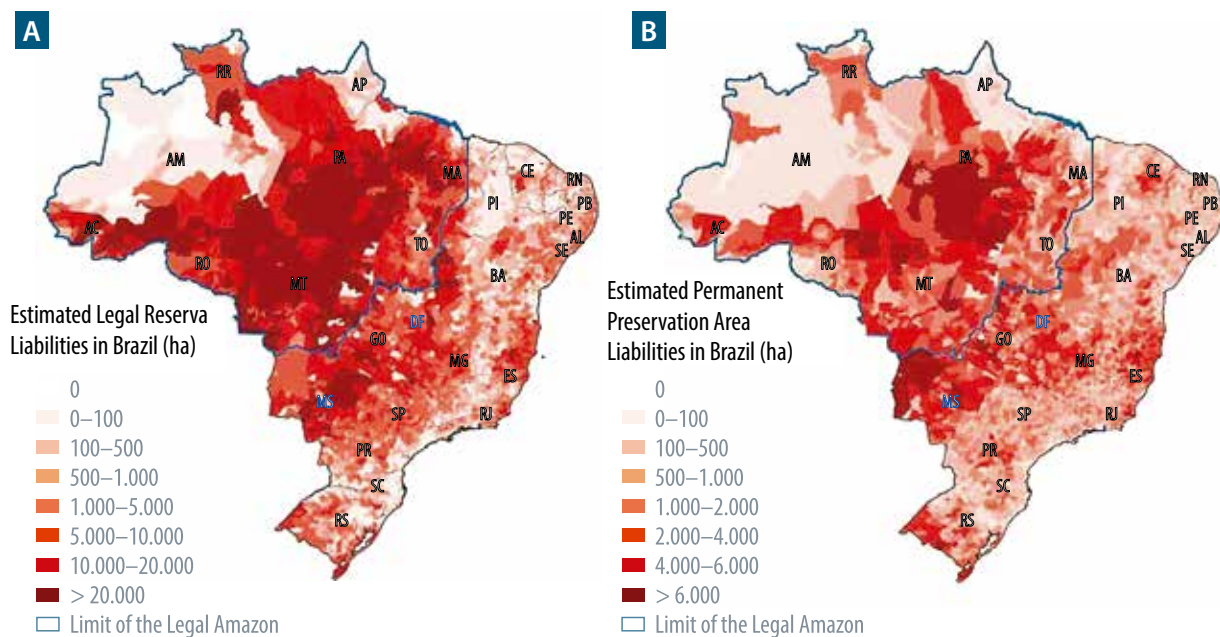
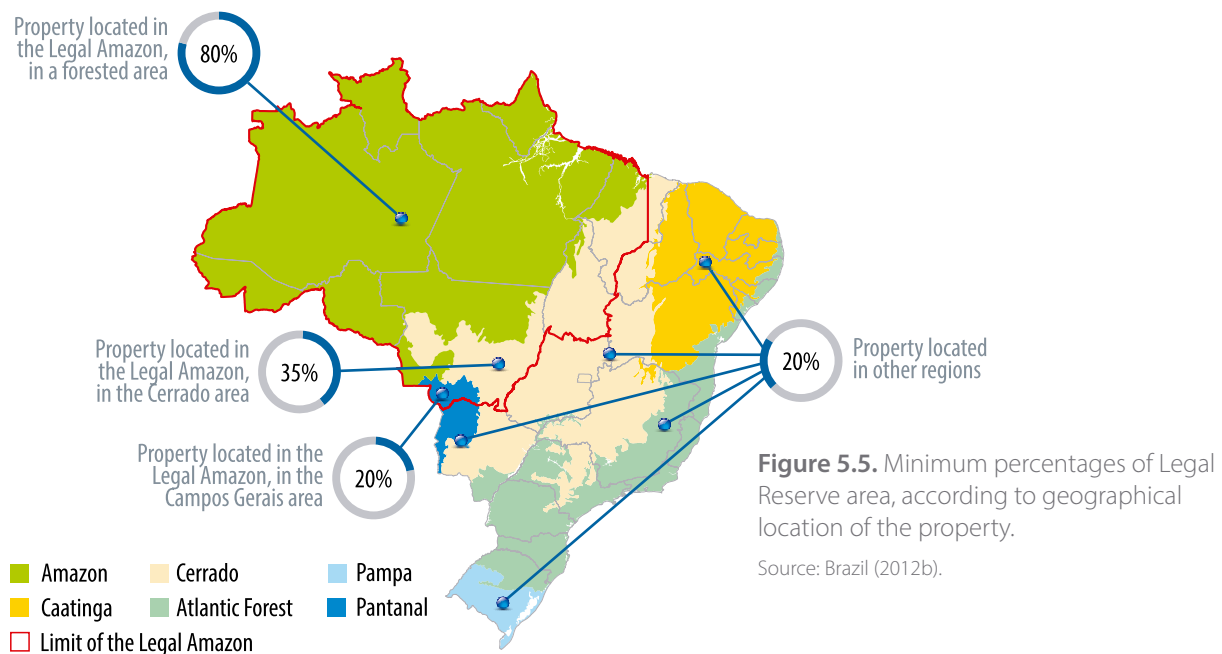


Figure 5.6. Distribution of liabilities in Legal Reserves (A) and Permanent Preservation Areas (B) in Brazilian municipalities.

Source: Observatório do Código Florestal (2025).

In the case of RLs, most of the deficit is concentrated in the Amazon, which accounts for more than 50% of the total, with around 9.5 million hectares, followed by the Cerrado biome (5.5 million hectares), Atlantic Forest (2.5 million hectares), Caatinga (351,000 hectares), Pampa (225,000 hectares), and Pantanal (40,000 hectares). For APPs, the largest liabilities are found in the Atlantic Forest, estimated at around 1 million hectares, followed by the Cerrado (930,000 hectares), Amazon (650,000 hectares), Caatinga (290,000 hectares), Pampa (116,000 hectares), and Pantanal (51,000 hectares).

Brazil has made several international and national commitments to reforestation and forest restoration, especially since 2015. In that year, within the scope of the COP12 in Paris, the country committed to restoring 12 million hectares of native vegetation by 2030, as part of its first Nationally Determined Contribution (NDC) (Brasil, 2015). In the NDC update presented at the COP29 in 2024 in Baku, Azerbaijan, Brazil reaffirmed the importance of forest restoration as a key strategy for achieving climate neutrality by 2050 (Brasil, 2024a). This orientation has been reinforced in internal policies, such as the updating of the Plano Nacional de Recuperação da Vegetação Nativa (National Plan for the Recovery of Native Vegetation, PLANAVEG) (Brasil, 2024b), which maintains the goal of recovering 12 million hectares by 2030 and aims to accelerate and expand restoration actions in the country. The commitment to environmental restoration is also included in the Low Carbon Agriculture Plan (ABC+ Plan (2020-2030) (Brasil, 2021), which includes among its goals planting forests on 4 million hectares by 2030, with the potential for mitigating 510 million Mg CO₂eq of GHG emissions.

Examples of the potential for GHG mitigation through actions to restore degraded or altered areas in the state of Minas Gerais have been pointed out by Oliveira et al. (2024c), who

estimated that restoration of 6.14 million hectares in the state has the potential to sequester 170 million tons of CO₂ by 2050. Silva (2024), in turn, estimated that restoration of just 1 hectare in the Atlantic Forest can contribute to the removal of 37 to 221 tons of C, the equivalent of removing 136 to 809 tons of CO₂, respectively, by 2030.

Embrapa has dedicated its efforts to supporting the fulfillment of Brazil's commitments, offering products, processes, and services intended to recover degraded or altered areas. One emblematic example was the creation of the RestauraBio network, which brings together around 140 professionals from the company who work on ecosystem restoration. Embrapa has also developed and improved tools to support these actions, such as the WebAmbiente Platform (Embrapa, 2025), designed to carry out diagnoses of degraded or altered areas that are being restored, and the Agrotag VEG System (Agrotag, 2025) for monitoring areas under restoration, to name just two examples.

Commitments between landowners/landholders and state environmental agencies to remedy any environmental liabilities are underway through adherence to the Programas de Regularização Ambiental (Environmental Regularization Programs, PRA) of the states and the Federal District. In broad terms, defining the best strategies to recover degraded or altered areas takes into account previous diagnoses to determine the levels of degradation observed, with reference to potential for natural regeneration in these areas and the activities needed to avoid, contain, or mitigate the factors causing the degradation. Figure 5.7 shows a summary of the approach adopted to define the best restoration strategies, taking into account the legal alternatives and the initial conditions of the areas to be restored.

Restoration can take place for the sole purpose of restoring ecological processes (ecological restoration), or it can include economic

Condition of the area to be restored	Disturbed or altered		Degraded
Potential for natural regeneration	High	Medium	Low
Restoration alternatives, in accordance with Law 12.651/2012	Encourage natural regeneration	Plant native species, together with encouraging regeneration of native species	Plant native species
	Intersperse woody, perennial, or long-cycle exotic species with regionally-occurring native species in up to 50% of the total area to be restored		
Restoration strategies	Passive restoration: control the degrading factors	Managed regeneration and/or partial plantings for densification, enrichment, or creation of "forest islands"	Planting in the entire area: direct seeding and/or planting of seedlings or cuttings
Control of degrading factors	Fence the area, control competing plant species, control leafcutter ants, control fire, eliminate erosive processes, and recover soil fertility		

Figure 5.7. Restoration strategies for degraded or altered areas, based on legal alternatives and the conditions of disturbance in the areas to be restored.

Source: Adapted from Skorupa et al. (2021).

exploitation of the areas in a productive approach for products that include grains, fruits, seeds, and fibers (productive restoration) in agroforestry systems.

Technologies and production systems that mitigate greenhouse gas emissions from irrigated rice cultivation in Brazil's temperate and tropical climate regions

Rice is essential for global food security, and occupies around 168.4 million hectares worldwide, which is equivalent to 9% of cultivated land (Silva; Wander, 2025). Production of this crop is directly linked to GHG emissions. The magnitude and pattern of these emissions are mainly determined by the water regime, inputs of organic material and synthetic nitrogen fertilizers, as well as soil management practices and the characteristics of the rice plant (Yan et al., 2005; Hussain et al., 2015). CH₄

is generated by the decomposition of organic matter in the soil under waterlogged conditions (Le Mer; Roger, 2001; Conrad, 2002). Emission of N₂O comes from the microbial transformation of N in the soil, and is favored by alternating periods of waterlogging and drainage (Reddy; DeLaune, 2008). Meanwhile, CO₂ emissions result from agricultural operations, such as soil preparation and the use of synthetic inputs. Globally, rice cultivation contributes 30% of CH₄ and 11% of N₂O emissions associated with agriculture (Intergovernmental Panel on Climate Change, 2007).

In Brazil, irrigated rice production occupied approximately 1.16 million hectares during the 2022/2023 harvest, which corresponds to just 0.69% of the world's cultivated area (Agência Nacional de Águas e Saneamento Básico, 2024). Most is concentrated in the lowlands of the Southern region, which is home to more than

85% of the country's cultivated area. In recent years, the Northern region has emerged as a center for production of this grain, currently with 10% of Brazil's irrigated rice area (Embrapa Arroz e Feijão, 2024). This area, however, represents around 25% of the country's irrigated area and accounts for 40% of the volume of captured water.

To mitigate these impacts, public policies must encourage sustainable agricultural practices that include efficient water management and low GHG emission cultivation strategies. Promoting C capture by the soil can balance the need for production with environmental preservation, ensuring a more sustainable agricultural system.

Evolution in management practices, selection of adapted cultivars, and adaptation of production systems have been decisive in directing research, development, and innovation actions to reduce GHG emissions in irrigated rice production. Embrapa and its partner institutions have conducted studies to monitor environmental impacts and identify opportunities for mitigation, ensuring greater sustainability for the production

sector. Scientific efforts began around two decades ago in the temperate climate region, with a special focus on Rio Grande do Sul, the country's main rice-growing center. With production growth in the Midwest, research expanded to tropical regions to accompany this increase in cultivated area and adapt management strategies to the new soil and climate conditions.

Table 5.3 summarizes the main results related to mitigating GHG emissions in irrigated rice production.

Advances in the quantification of GHG emissions from irrigated rice production have made it possible to identify different mineral sources of N with lower N₂O emissions compared to urea (which is typically applied), and determine specific N₂O and NH₃ emission factors for the soil and climate conditions in the Southern region of Brazil, the country's main producer of rice.

Urea protected with a urease inhibitor (NBPT) and urea treated with a nitrification inhibitor (DCD), for example, have lower N₂O emissions

Table 5.3. Technological solutions for reducing greenhouse gas (GHG) emissions in irrigated rice production in Brazil.

Management or practice	Result for reduction of GHG emissions
Water management	Irrigation via intermittent flooding, furrows and sprinkler use have GHG emission mitigation potential of more than 70% compared to continuous flooding.
Nitrogen fertilization	Using more efficient fertilizers reduces GHG emissions compared to traditional soluble sources.
Crop diversification	Rotating rice with rainfed crops (soy, corn, sorghum, forage) reduces GHG emissions compared to rice monoculture.
Rice cultivars	Identification of cultivars with lower CH ₄ emissions due to genetic diversity, reflecting differences in production, oxidation, and transport of this gas.
Soil management and mulch	Early soil preparation in the fall and rotation with soybeans reduce annual GHG emissions in lowland areas more than fivefold compared to conventional preparation in the spring.
Sustainable production systems	Rotation or succession of rainfed crops on broad elevated rows using no-till planting, combined with improved pastures and rotational grazing, reduces CH ₄ emissions and increases C accumulation in the soil.
Irrigated soy/rice rotation	Keeping the soil drained for longer (soybean/soybean/irrigated rice) reduces CH ₄ emissions from rice by up to 30%, a better outcome than simple soybean/irrigated rice rotation.

than plain urea, with losses of 1.96 and 2.87% of the N applied, respectively.

Emission of N_2O is the main route of N loss from the soil-plant system in irrigated rice crops, while NH_3 volatilization is less significant, and mainly occurs during applications in the early stages of crop development. It is important to note that the NH_3 emission factors determined for irrigated rice cultivation in southern Brazil were much lower than the IPCC reference value (10%), indicating a lower contribution from this route to N losses in the region.

Brazil's 3rd National Communication to the United Nations Framework Convention on Climate Change was published in 2016 (Brasil, 2016), followed by the 4th National Communication in 2020 (Brasil, 2020), with technical coordination by Embrapa and supervision by the Ministry of Science, Technology, Innovation and Communications (MCTI). In both editions, estimates of CH_4 emissions from rice cultivation for the state of Rio do Grande do Sul were calculated based on local emission factors, replacing the standard data proposed by the IPCC and used in previous versions. This change provided a more realistic estimate of the national emissions scenario in relation to irrigated rice cultivation.

Management practices and production systems that mitigate GHG emissions in irrigated rice cultivation have been developed in order to maintain or expand productivity and efficiency in the use of natural resources and inputs. In this way, the resulting strategies not only yield significant environmental gains, but are also linked to technical and economic benefits, guaranteeing sustainability and competitiveness for national production and putting it on a par with (or even above) other producing countries.

The mitigation technologies described here also offer various benefits related to adaptation, such as identification of irrigated rice cultivars

that use water more efficiently and are adapted to grow in an environment with less water. Also worth mentioning are the adaptation benefits of diversifying production systems, such as the reduction of the weedy rice seed bank, which is the most significant limiting factor in rice farming today; minimizing the occurrence and negative impact of the main rice diseases (particularly brusone or rice blast fungus) as well as insect pests; promoting nutrient cycling; contributing N to the system via BNF; and reducing the crop's demand for fertilizer.

The GHG-mitigating technologies and production systems developed for the national rice sector have broadly sought to promote gains in sustainability and boost production in lowland areas. These technological innovations aim to reconcile the maintenance of biodiversity and other ecosystem services associated with agroecosystems with expanded production of rice, other grain crops, fodder, meat, and milk, strengthening the regional economy and national food security in line with Brazil's commitments to reduce GHG emissions as part of the Paris Agreement.

Production systems of local or regional importance

The diversity of agricultural and forestry production systems in Brazil reflects the diversity of the biomes, cultures, and knowledge present across its vast territory. Notable among these systems are those of local or regional importance, which were developed and adapted to the ecological, social, and economic conditions in certain territories (Buainain; Garcia, 2013; Balieiro et al., 2024). Although in many cases they are not widely known, valued, or included in large-scale markets, these systems have played important roles in their contexts, where they contribute to food security, biodiversity conservation, income generation, and strengthening resilience to climate change (including mitigation of GHG

emissions), and are therefore recognized in important public policies (Brasil, 2021, 2024a, 2024b; Perin et al., 2021).

These systems contribute not only by offering differentiated products with high added value (such as those produced in agroforestry systems, or from use and management of native vegetation), but also by promoting a production model that more efficiently uses natural and economically viable resources. By combining social and technological innovation, value of traditional knowledge, and ecosystem preservation, these systems strengthen territorial identity and bolster the country's ability to compete with sustainable products in markets that are increasingly demanding in terms of traceability and socioenvironmental responsibility (FAO, 2020).

From the viewpoint of risk management, agroforestry systems (including those based on agroecology) significantly reduce producers' vulnerability to extreme climatic events, pests, and market fluctuations, since they include a diversity of native and cultivated species that can be managed to provide more stable production, diluting economic and ecological risks. These systems also enhance the adaptive capacity of rural communities, allowing solutions to be shaped locally and adjusted to changes over time (Brasil, 2021).

On the global stage, these systems have a significant impact on the sustainability of food production. Adoption and enhancement of systems like those presented in the following case studies represent concrete ways to contribute to GHG mitigation, recovery of degraded soils, increased productivity without converting new areas, and biodiversity conservation (Intergovernmental Panel on Climate Change, 2019). In regions such as the Amazon, Cerrado, and Caatinga biomes that face growing pressure on ecosystems,

these experiences point the way to low C development, generating jobs and income.

These production systems demonstrate positive externalities, especially in a context where international trade is paying increasing attention to socioenvironmental requirements. Products from sustainable systems can access niche markets, foster fairer and more transparent value chains, and contribute to global targets for tackling land degradation and the climate crisis (Intergovernmental Panel on Climate Change, 2019; Organization for Economic Cooperation and Development, 2023).

Brazil has led important efforts to promote sustainable agricultural production, including systems of local and regional relevance. Initiatives such as the Plano Setorial para Adaptação à Mudança do Clima e Baixa Emissão de Carbono na Agropecuária (Sectoral Plan for Adaptation to Climate Change and Low Carbon Emissions in Agriculture and Livestock, also known as the ABC+ Plan) (Brasil, 2021), Plano Nacional de Recuperação da Vegetação Nativa (National Plan for the Recovery of Native Vegetation, PLANAVEG) (Brasil, 2024b), Programa Nacional de Redução de Emissões por Desmatamento e Degradação (National Program for Reducing Emissions from Deforestation and Degradation, REDD+) (Brasil, 2025), Programa Bioeconomia Brasil – Sociobiodiversidade (Bioeconomy Brazil – Sociobiodiversity Program) (Brasil, 2024c), Programa Nacional de Florestas Produtivas (National Program for Productive Forests) (Brasil, 2024d), Programa de Aquisição de Alimentos (Food Acquisition Program, PAA) (Perin et al., 2021), Programa Nacional de Fortalecimento da Agricultura Familiar (National Program to Strengthen Family Farming, PRONAF), and the strengthening of payment policies for environmental services are directly related to the local and regional systems addressed herein, and indicate that the country is investing in solutions that extend beyond large-scale production

systems or momentary trends imposed by external markets. The ABC+ Plan, for example, encourages practices such as agroforestry systems and recovery of degraded areas including APPs and RLs, just as the Programa Nacional de Florestas Produtivas (National Program for Productive Forests, PNFP) supports the recovery of degraded or altered areas for productive use, contributing to regularization and environmental suitability in family farming and expanding production of healthy food and products from social and biological diversity. PLANAVEG, in turn, establishes ambitious restoration targets with sustainable production models. In a complementary manner, REDD+ recognizes the role of extractive communities in forest conservation, the Bioeconomia Brasil program values products from social and biological diversity, and PAA and PRONAF work to ensure a market and financing for family farming. Finally, the success and strengthening of these systems shows that leadership also comes from the grassroots, from farmers, extractivists, and traditional communities who develop, innovate, and maintain sustainable ways of living and producing in the countryside.

Technological solutions that contribute to low carbon emissions in agricultural production systems and for monitoring, reporting, and verifying the results of technologies in the ABC+ Plan

This section discusses technologies that are not production systems but nevertheless play a fundamental role in the success of the ABC+ Plan (Brasil, 2021). These technologies both enable or increase the mitigation and adaptation capacity of the various production systems, and also make it possible to monitor, report, and verify (MRV) the impacts of these systems. They are essential, due to Brazil's need to prove the

emission reduction targets it assumed in its NDC, as part of the Paris Agreement. MRV tools are also indispensable for meeting society's expectations in the face of global change, considering the risks and opportunities that markets tend to demand, risks related to new production standards and regulations that may be required by markets, and opportunities arising from the C economy, with the adoption of technologies that store C in the soil and landscape.

Inoculants in grain crops

Application of inoculants containing bacteria that promote plant growth is one strategy that combines tradition and innovation in Brazilian agriculture. These microorganisms play a fundamental role in BNF and plant growth, directly helping to reduce use of synthetic nitrogen fertilizers. Production of these fertilizers requires high energy consumption, and is associated with significant GHG emissions. In contrast, BNF uses bacteria that can convert atmospheric N into forms that can be assimilated by plants, presenting a sustainable and efficient alternative with the potential to reduce environmental impacts and boost the sustainability of agricultural production systems. As a result, the use of BNF in soybean cultivation (with over 40 years of history in Brazil) is considered one of the pillars of "tropical agriculture," since recurrent inoculation provides the N input required for this crop without the need for synthetic fertilizers (Hungria; Nogueira, 2022).

The Brazilian industrial sector that produces inoculants currently has over one hundred production facilities. Over 600 products are registered with the Ministry of Agriculture and Livestock (MAPA), and more than 100 million doses of inoculants are sold each year for application over roughly 45 million hectares. The main crop that benefits is soybeans, with an area of more than 30 million hectares inoculated

annually, followed by corn with around 7 to 8 million hectares, and sugar cane, with approximately 1.5 million hectares. Additionally, co-inoculation has also recently been considered capable of promoting low N₂O emissions and high yields of common beans, a staple food for the Brazilian population, especially when cultivated using only bioinputs for BNF in a crop-livestock integration system (Schulman et al., 2025).

In order to understand the potential of technologies based on growth promoting bacteria, it is necessary to understand the different aspects of inoculants. Nitrogen-fixing bacteria (collectively called rhizobia, including many genera such as *Bradyrhizobium* and *Rhizobium*) are capable of establishing symbiosis with leguminous plants such as soybeans and beans to form root structures called nodules, where N fixation occurs. Symbiosis between soybeans and *Bradyrhizobium* provided via inoculants contributes around 90% of the N needed by the crop (Hungria; Nogueira, 2022); annual re-inoculation in this crop leads to average increases of 8 to 10% in grain yield. These gains in turn generate savings of around USD 15 billion per year in Brazil (Telles et al., 2023), as well as significant environmental benefits. Estimates indicate that over 300 kg of CO₂eq each year is no longer emitted for each hectare of soybean cultivation, demonstrating that BNF plays a fundamental role in mitigating GHG emissions from Brazilian agriculture (Santos et al., 2019; Prando et al., 2024). According to IPCC data, for every 1 kg of N applied to agriculture, around 10 kg of CO₂eq gases are emitted.

Another technology that is also based on N-fixing bacteria, but without the ability to establish symbiosis, involves strains of *Azospirillum* and *Nitrospirillum*. This research began in Brazil more than 50 years ago with pioneering studies by the researcher Johanna Döbereiner, although the first commercial products have appeared more

recently. In Argentina, inoculants containing *Azospirillum* were first marketed more than 20 years ago, while in Brazil this happened just over a decade ago. These bacteria have low specificity in their association with plant hosts, and in addition to their ability to fix N they perform a series of mechanisms to promote the growth of plant roots and aerial parts (Santos et al., 2019). This leads to improved plant performance, especially in terms of fertilizer use. Recent estimates indicate an improvement of up to 20% in N use efficiency (Santos et al., 2019). Although *Azospirillum* was initially recommended for corn, significant results have also been obtained with co-inoculation with *Bradyrhizobium* in soybean crops, a practice which combines high N input and better use of nutrients in general (Hungria et al., 2015; Jantalia et al., 2021; Barbosa et al., 2022). In the specific case of *Nitrospirillum*, a bacterium that comprises inoculants for sugarcane, similar results were obtained to those seen in corn (Reis et al., 2020).

Other inoculants have been introduced to the Brazilian market more recently, such as those containing different species of *Bacillus*, which are recommended for mitigating plant water stress and improving the use of phosphorus (P) in the soil (Oliveira-Paiva et al., 2024). In this case, the use of P-solubilizing *Bacillus* has shown positive responses in promoting better use of this nutrient, which is immobilized in the soil. Only 15 to 20% of the P applied to tropical soils (like those in the Cerrado biome) is actually used by the plants, and the rest is retained in the soil. By facilitating mobilization of this P for crops, such inoculants permit both economic returns due to the need for lower doses of fertilizers and environmental benefits by reducing demand for production and transport of these inputs.

The successful use of *Azospirillum* has paved the way for advances in research to identify other microbial-based technologies for agriculture, stimulating the industry to develop and register

new inoculant products and encouraging producers to adopt these innovations. Recently, inoculants with a consortium of *Azospirillum* and *Pseudomonas* bacteria have been launched to boost biomass production in pastures (Hungria et al., 2021), along with inoculants containing *Bradyrhizobium*, *Bacillus*, and *Paraburkholderias* for soybeans, in products that integrate BNF, promote plant growth, and protect seedlings (Fernandes et al., 2021).

Research into bioinputs has made significant advances as it seeks to improve the efficiency of inoculants for different crops and develop more precise methodologies for quantifying BNF. Recent strides in research include the launch of new commercial strains, as well as scientific validation that bioinputs used in Brazilian conditions can reduce GHG emissions by up to 60%. The inclusion of bioinputs in the Plano Nacional de Fertilizantes (National Fertilizer Plan) (Brasil, 2023c) reinforces Brazil's commitment to low C agriculture. This plan's goals include increasing the adoption of bioinputs for plant nutrition, expanding the supply of biological products that promote efficient use of fertilizers, and reducing gaseous losses of N (N_2O and NH_3) in agriculture.

In summary, the inoculation of crops with beneficial microorganisms validated by research represents a consolidated and strategic technology for Brazilian agriculture that offers significant economic, environmental, and social benefits. Research and development involving bioinputs, combined with effective public policies, are fundamental for Brazil to continue making progress in sustainable agricultural production and climate change mitigation.

Enhanced efficiency fertilizers – organomineral and specialized nitrogen fertilizers

Fertilizers are essential inputs for agriculture, since they provide the nutrients required for

plant production. Brazil is the world's fourth largest consumer of fertilizer, and relies heavily on imports of these products. Most Brazilian agricultural soils are nutrient-poor and require large amounts of fertilizer; without these inputs, the land area required needed to achieve Brazil's current food production levels would increase by at least 40%. In this way, fertilizers help reduce the need to clear new areas, which should be considered in their C footprint. However, the process of producing fertilizers, especially nitrogen fertilizers, is a major source of GHG emissions. The nitrogen fertilizer industry has been working for many years on practices to reduce emissions of pollutants and GHGs, which has significantly reduced its C footprint.

In recent decades, with the growing interest in decarbonizing agricultural practices, the need has arisen to develop more efficient fertilizers that result in lower GHG emissions. The industry, in response to this demand, has started to optimize its industrial processes and offer fertilizers with added technologies in order to optimize nutrient delivery and reduce N losses through ammonia volatilization. Notable within this context are nitrogen fertilizers which are protected or enriched with inhibitors of chemical processes that lead to these losses.

Another important development is organomineral fertilizers, which use organic waste in their composition. These products contribute to proper reutilization of substances that could otherwise cause negative environmental impacts. As a result, organomineral fertilizers not only reduce dependence on mineral sources, but also minimize the environmental impacts associated with the inappropriate disposal of this waste.

The use of fertilizers with a lower environmental impact reduces the impact of the entire production system, resulting in products with a lower C footprint and making food production more sustainable. All fertilizer technologies

validated in Brazil can readily be extended to other tropical agricultural countries such as those in Africa and Latin America, which have soils and climates similar to Brazil.

Organomineral fertilizers

Organomineral fertilizers are obtained from the combination of mineral fertilizers and organic sources, which can be organic waste from all types of origins. Using organic waste from agricultural, agroindustrial, or livestock sources to produce organomineral fertilizers is one strategy to recover the nutrients contained in this waste and dispose of it correctly, thus reducing its potential environmental impacts. This makes it possible to utilize waste that would otherwise be applied in its raw state, involving huge amounts of energy for transportation and application as well as generating a large amount of GHG, in a more economical and ecological way.

Brazil is a major producer of meat, especially pork and poultry. These activities generate large amounts of waste which, if not properly disposed of, can negatively impact the environment through water contamination and GHG emissions (Alves et al., 2012). It is estimated that Brazil produces around 8 million tons of poultry litter and 105 million cubic meters of pig waste every year (Benites et al., 2010). Considering the nutrient content (NPK) of this waste, this represents around 20% of the country's demand for nutrients. Use of these materials to produce organomineral fertilizer represents an important step towards reducing Brazil's external dependence on imported fertilizers and mitigating GHG emissions compared to direct use of waste in its natural state.

Modified urea

Urea is the most widely used source of N in Brazil, and accounts for approximately 50% of the total consumed in the country each year. Before making assimilable forms of N available to plants,

urea undergoes enzymatic hydrolysis catalyzed by urease, a natural enzyme.

In the hydrolysis process, alkalization occurs around the urea granules, which induces N losses to the atmosphere through ammonia volatilization. These losses represent 20% of the N applied in the form of urea, on average, at least double the quantity observed for other types of fertilizer such as ammonium sulfate and ammonium nitrate (Mazzetto et al., 2020). These authors also concluded that emissions of N_2O , a potent GHG, are higher when urea is used. It is important to consider that volatilized ammonia is an indirect source of N_2O after it is deposited in the soil (Alves et al., 2012).

A number of solutions have been developed to reduce urea waste and minimize its environmental impacts. One strategy is to coat the urea grains with materials such as polymers or elemental sulfur, which act as physical barriers, and promote gradual release of the nutrient into the soil. This controlled release prevents too much N from being lost in the air as a gas. In some cases, N losses can be controlled with relatively high efficiency. One study in Sergipe, for example, compared different forms of urea (Santos et al., 2020). The findings indicated that application of an organomineral fertilizer, composed of urea combined with organic materials, reduced N losses by up to 74% in one harvest and 67% in the following harvest compared to ordinary urea and ammonium sulfate. However, urea coated with sulfur showed variable results: in one harvest it reduced losses by 53%, but in another it recorded higher losses than ordinary urea. This indicates that although this technology is promising, challenges still remain to ensure consistency in its effectiveness.

One alternative to reduce N losses and the environmental impacts caused by the use of urea as a fertilizer is the application of substances that slow the natural chemical process that releases N from urea into the soil. These substances

include inhibitors of urease (an enzyme that transforms urea into ammonia) such as N-(n-butyl) thiophosphoric triamide (NBPT), which are sometimes combined with inhibitors that prevent other N losses via denitrification or nitrate leaching. The most common nitrification inhibitors are dicyandiamide (DCD), nitrapyrin (2-chloro-6-(trichloromethyl) pyridine), and 3,4-dimethylpyrazole phosphate (DMPP) (Mazzetto et al. 2020). One of these combinations, NBPT and nitrapyrin, reduced N₂O emissions by 49% after the fertilizer was applied to a cornfield. Use of NBPT alone, on the other hand, made it possible to reduce N losses in the form of ammonia by up to 35% (Martins et al., 2017), which represents a significant reduction in indirect N₂O emissions resulting from the subsequent atmospheric deposition of ammonia. Additionally, applying urea mixed with inhibitors allows the plants to make better use of the fertilizer, resulting in a significant increase in grain production of over 1.5 tons per hectare compared to the conventional use of urea.

Although urea is widely used in Brazilian agriculture as a fertilizer, its conventional use is associated with N losses, with direct implications for fertilizer use efficiency and increased GHG emissions. In this way, the refinement of technologies to produce improved urea-based fertilizers represents a concrete opportunity to combine gains in agronomic efficiency with a reduction in the environmental impact of nitrogen fertilization.

Biochar: a technological alternative with potential for additionality in the carbon market, soil improvement, and recovery of degraded lands

Using pyrolysis and biorefinery byproducts in agriculture opens up new possibilities for sustainable soil and waste management (Novotny et al., 2015). Pyrolysis is a process that heats biomass without sufficient oxygen for

combustion, transforming it into biochar, a type of charcoal. The biomass used is byproducts of processes involving production of renewable energy (heat, electricity, and biofuels) and the manufacture of petrochemical substitutes such as polymers, plastics, and agroindustrial inputs. Biochar has a high concentration of C, in a form that is very resistant to decomposition (recalcitrant). When put into the soil, it can remain there for hundreds or even thousands of years, offering benefits for soil fertility (Madari et al., 2017; Rodrigues et al., 2019) and nutrient and water retention (Carvalho et al., 2014), as well as filtering out pesticides (Pierri et al., 2022) and toxic elements (Wnetrzak et al., 2014). It is a technology that can be applied on different scales, in both the production and application of biochar (Latawiec et al., 2019). Inspired by pre-Columbian indigenous knowledge (Novotny et al., 2009), this technology combines tradition and science in the pursuit of sustainable agriculture (Dela Piccola et al., 2021).

Biochar technology was inspired by studies on Amazonian terra preta soils (Novotny et al., 2007). These soils are extremely fertile and rich in C (Sombroek et al., 1993; Cunha et al., 2007), demonstrating remarkable resilience by maintaining their fertility even after prolonged agricultural use. This characteristic is mainly due to humification, a process that transforms and incorporates organic materials (including carbonized material) into the organic matter of soils. Terra preta soils were formed by pre-Columbian indigenous peoples, although it is not clear whether they originated from an intentional process of soil improvement or were simply the result of their agricultural and housing practices (Lombardo et al., 2022). These populations habitually disposed of their everyday waste (food scraps, animals, turtle shells, and excrement) in bonfires, possibly to avoid insect proliferation and attracting predators. This resulted in the significant accumulation of carbonized materials, ash, and charcoal in the soil. Over time, the

natural chemical alterations of this carbonized waste resulted in a recalcitrant material that is capable of retaining essential nutrients for plant growth, thanks to the formation of reactive chemical groups. This retention prevents the loss of nutrients, making terra preta soils extremely productive, even in an Amazonian environment subject to intense rainfall and weathering. Weathering is the natural process that wears down and transforms rocks over time, helping to form soil. It occurs through the forces of nature, such as rain, wind, heat, and even the action of plants and microorganisms. Most soils in tropical climates are highly weathered, which means they have low natural fertility because many essential nutrients have been lost over time. In Brazil, latosols and argisols are common examples of this type of soil.

Research on terra preta soils made it possible to define a model of organic material that could be reproduced in order to improve soil fertility sustainably and sequester C (Novotny et al., 2009). This can be done by using carbonized waste (biochar) to generate the desired reactive chemical groups efficiently and economically, using modern techniques in a harmonious integration between traditional pre-Columbian indigenous knowledge, based on respect for nature and contemporary scientific knowledge.

Finally, it is important to note that this technology is not intended to compete for energy resources such as charcoal and sugarcane bagasse, but rather to optimize their use for generating energy or chemicals. This is done through modern pyrolysis methods and the use of waste that is difficult to dispose of, and often becomes an environmental liability. This includes waste from the wood, pulp and paper, and charcoal industries, as well as from manufacturing of second-, third-, and fourth-generation biofuels (such as biodiesel, ethanol from cellulosic processes, and biofuels derived from algae), along with sewage sludge, rice

husks, and other agroindustrial byproducts. In this way, energy and food production are reconciled with increased soil fertility and C sequestration. There are also environmental benefits to this approach, which transforms challenges into opportunities and promotes sustainable integration between the energy and agroindustrial sectors.

We may be on the cusp of a second Green Revolution, where outdated technologies will be replaced by innovative processes that value reuse of waste and produce new inputs adapted to tropical conditions. Since this is an unprecedented topic in the literature, and Embrapa researchers are pioneers in the field, the contributions are still mainly in the scope of advancing knowledge that already supports the development of more sustainable technologies to promote C sequestration and boost soil fertility, providing a better destination for agroindustrial waste.

Technologies to reduce enteric methane emissions

Ruminants are capable of utilizing large amounts of fiber and converting it into highly nutritious products for humans. Improving the conversion efficiency of fibrous foods into products such as milk and meat depends on multiple biological factors such as genotype and metabolism, and animal nutrition is closely related to the expected responses (Oliveira et al., 2025).³

However, for this process to take place, ruminants release CH₄ gas via eructation (belching); this is

³ OLIVEIRA, P. P. A.; BRUNO, J. F.; CHAMILETE, S. A. M.; FURTADO, A. J.; BRUNETTI, H. B.; NOVO, A. L. M.; ALVES, T. C.; NASSU, R. T.; BERNDT, A. Boas práticas para a mitigação da emissão de metano entérico em bovinos leiteiros. In: OLIVEIRA, P. P. A.; NOVO, A. L. M.; BERNDT, A.; NASSU, R. T.; ALVES, T. C. (ed.). Protocolos de boas práticas para a mitigação de gases do efeito estufa em sistemas de produção de bovinos. São Carlos: Embrapa Pecuária Sudeste, [2025?]. p. 8-42. In press.

one of the main GHGs from livestock activities. CH₄ is produced naturally within the rumen and reticulum of ruminants. It represents energy loss during digestion of food, and also has a negative impact on the environment.

In livestock systems in Brazil, enteric emissions of CH₄ often account for more than 90% of total GHG emissions. This fact requires urgent action to reduce emissions of this gas, which helps to facilitate forms of compensation for GHG removals (Oliveira et al., 2020). Furthermore, Brazil recently joined the Global Methane Pledge, which has a central objective of voluntary actions to collectively reduce global CH₄ emissions by at least 30% compared to 2020 levels by 2030. This measure has the potential to reduce global warming by up to 0.2 °C by 2050 (Global Methane Pledge, 2025).

Various institutions have been developing campaigns and policies to mitigate enteric CH₄ emissions, and much emphasis has been placed on nutritional management. However, the impact of activities to improve zootechnical indices related to production and reproduction on farms also has a major impact on CH₄ emissions, making them important strategies for mitigating GHG emissions (Oliveira et al., 2025).

According to Oliveira et al. (2025), various strategies related to nutritional management and rumen manipulation can be adopted and include grazing management, lipid supplementation, the use of essential oils, ionophores, seaweed, alternative electron receptors, secondary plant compounds, yeasts, and chemical inhibitors of methanogenesis, a process in which microorganisms generate CH₄.

Grazing management involves regulating the animals' access to pasture. Emission of CH₄ varies according to the quantity and quality of the food digested, and is generally greater when animals consume poorer quality food with lower energy density. In Brazil, Congio et al.

(2018) observed that pastures of elephant grass (*Pennisetum purpureum* Schum. cv. Cameroon) with the criterion of animals entering the pasture at 95% light interception, compared to maximum interception, yielded a 20% reduction in CH₄ emissions in grams per kilogram of milk produced.

Lipid supplementation, such as including seed oils in the diet of cattle, promotes mitigation of CH₄ through its toxicity to methanogenic microorganisms, reduction of the bacteria that consume CH₄, and changes in rumen fermentation, resulting in lower production and emissions of CH₄. In meta-analyses by Congio et al. (2021) and Arndt et al. (2022), decreases ranging from 17.6 to 47.9% were observed in enteric CH₄ emissions per animal, depending on the type and amount of lipid used in the animal's diet.

Essential oils are complex mixtures of secondary metabolites found in all living plant tissues, and can contain components such as eugenol (present in clove buds) or thymol and carvacrol (present in oregano). When these compounds are extracted and concentrated or produced chemically, essential oils can have antimicrobial effects on bacteria and fungi when they are added to the diet of cattle, especially gram-positive bacteria. In the rumen, these bacteria are involved in fermentation processes coupled with the production of CH₄ through the release of hydrogen gas (H₂) (Owens; Goetsch, 1988).

A commercial product based on oregano oil and green tea extract, and combinations of these oils fed to lactating dairy cows reduced CH₄ emissions by between 16 and 22% per kilogram of dry matter ingested (Kolling et al., 2018). And in a meta-analysis by Belanche et al. (2020), reductions of 8.8% in daily CH₄ production per animal, 12.9% per kilogram of dry matter ingested, and 9.9% in milk production (corrected for fat and protein) were reported for a mixture of

coriander, eugenol, geranyl acetate, and geraniol in dairy cows.

Ionophores, such as monensin, lasalocid, or salinomycin, are a class of additives that selectively depress or inhibit the growth of rumen microorganisms, indirectly reducing CH₄ production. In a meta-analysis by Appuhamy et al. (2013), dairy cows supplemented with monensin showed an average reduction of 3.6% (g/d) in CH₄ emissions.

Seaweeds, on the other hand, are macroalgae, complex and diverse organisms that can grow in marine and freshwater environments. When used in cattle feed, seaweed that produces and stores a substance called bromoform (a potent inhibitor of the methyltransferase enzyme) can reduce production of CH₄. Studies on sheep, steers, and dairy cows have reported reductions ranging from 9 to 98% in CH₄ production with the use of dietary supplementation containing *Asparagopsis* spp. This variation depends on the supplementation dose and type of diet used (Roque et al., 2019, 2021; Stefenoni et al., 2021). The effectiveness of *Asparagopsis* spp. in mitigating CH₄ depends on its concentration of bromoform, which varies from 3.0 to 51.0 mg/kg of dry matter. Furthermore, *Asparagopsis* spp. is more effective at decreasing CH₄ production in high-concentrate diets than in high-forage diets (Roque et al., 2021). However, as Hristov (2024) points out, after compiling the work of Stefenoni et al. (2021), Thorsteinsson et al. (2023), and Krook et al. (2024), care must be taken with the quality of milk from cows fed macroalgae, since they can contain high concentrations of iodine, arsenic, and other heavy metals or toxic elements. Although technologies are being developed to reduce some regulated elements such as iodine, precautions are required.

Alternative electron receptors are organic compounds such as fumarate and malate, and inorganic compounds such as nitrate and sulfate. Nitrate in particular captures hydrogen in the

rumen, competing with the formation of CH₄ and consequently helping to reduce it. It is important to remember that nitrate is potentially toxic, and the diet needs to be adapted or readapted if its use is discontinued. A meta-analysis by Feng et al. (2020) estimated an average reduction of 13.9% in CH₄ production for the average nitrate dose. And Arndt et al. (2022) observed that the inclusion of fumarate and nitrate as alternative electron receptors decreased total CH₄ production by 16 and 17%, respectively.

Secondary plant compounds, such as tannins and saponins found in various leguminous and non-leguminous plants, have the potential to reduce CH₄ emissions by directly or indirectly inhibiting methanogenic microorganisms and some specialized fibrolytic bacteria, which can compromise fiber digestion. The use of effective plant sources for enteric CH₄ mitigation that contain tannins and/or saponins, such as *Leucaena* spp., *E. cyclocarpum*, and *G. sepium*, is particularly important for grazing systems, especially during the dry season when overall pasture quality is low (Congio et al., 2021). These authors state that inclusion of 27% (dry weight) *Leucaena* spp. in diets predominantly composed of grasses decreased the CH₄ yield per kilogram of dry matter ingested and the Y_m factor by 27.4 and 29.6%, respectively, without affecting daily CH₄ production, emission intensity per liter of milk, or milk production. The meta-analysis by Arndt et al. (2022) found that the inclusion of tanniferous fodder in the diet of ruminants reduced the intensity of CH₄ emissions associated with milk production by 18%.

Yeasts, mainly of the *Saccharomyces* genus, are fungi that work by modifying rumen fermentation in two ways: by factors that stimulate rumen bacteria, and by absorbing oxygen that enters the rumen environment. This process increases fermentation efficiency and favors the production of propionate; greater volume of this substance is directly related to

a reduction in CH₄ emissions. Although not all studies point to significant reductions in CH₄ emissions from yeast supplementation (Darabighane et al., 2019; Palangi; Lackner, 2022), there is evidence of beneficial effects under certain conditions. Tristant and Moran (2015), for example, observed a 4% (g/day) reduction in CH₄ production in lactating Holstein cows kept in confinement and supplemented with *S. cerevisiae* at a dose of 5 x 10⁷ CFU/kg of dry matter.

Synthetic chemical inhibitors of methanogenesis such as 3-nitrooxypropanol (3-NOP) are low-molecular-weight molecules that, when included in small doses in ruminant feed, inhibit CH₄ production by blocking the final stage of its formation in the rumen. At typical levels included in high-concentrate diets for dairy and beef cattle, 3-NOP reduced CH₄ production by 30% (Hristov et al., 2015; Arndt et al., 2022; Beauchemin et al., 2022).

In Brazil, several of these strategies are being successfully adopted in order to comply with the Global Methane Pledge and improve the results of the National Inventory of Greenhouse Gas Emissions and Removals. Within this context, Embrapa frequently conducts evaluations to verify the effect of these strategies in tropical conditions.

MRV Protocol in Brazilian agriculture

The MRV (measurement/monitoring, reporting and verification) Protocol was developed conceptually by Embrapa and the Getulio Vargas Foundation (FGV) (Gurgel et al., 2020) to validate information on various agricultural production systems in a way that is applicable to all Brazilian biomes and makes it possible to continuously obtain data from rural properties. This approach permits management of the results and impacts of actions to tackle climate change, and is useful for planning projects, making investment decisions, generating C credits, setting targets, and outlining climate strategies. The protocol

is aligned with UNFCCC guidelines (Wilkes et al., 2013; Intergovernmental Panel on Climate Change, 2019), providing reliable information on changes in soil C stocks and GHG emissions/removals on farms that adopt sustainable production systems (SPS).

The protocol can be applied to various agricultural systems, including annual and perennial crops (food, fiber, fodder, and bioenergy), animal confinement, manure treatment, and integrated livestock-forest and crop-forest systems. Developed from a conceptual model, the protocol integrates local and remote data collection tools, multiple-use databases, and remote calculation and verification methods.

One of the main tools associated with the protocol is the GHG Protocol Agriculture and Livestock calculator, which is also available in a web version, applied to the balance of emissions from scopes I (direct emissions from the company's own operations) and II (indirect emissions associated with energy purchased by the company). This tool has been updated to include emissions from cattle feedlots and the forestry component. The emission coefficients were revised according to the National Inventory of Greenhouse Gas Emissions (Brasil, 2020) and based on the most recent scientific literature (Manzatto, 2024).

The protocol applies to producers of different sizes. Although medium-sized and large units have more commercial interest due to potential economic advantage, small producers can also benefit from validating good practices and monitoring the evolution of their systems in comparison with other establishments.

Notably, the protocol was developed based on tools that are already available but are now integrated and automated for collecting, recording, and verifying data on farms. These tools include:

Sistema de Apoio à Caracterização de Imóveis Rurais (the System for Supporting Characterization of Rural Properties, SACIR):

a web platform that generates cartograms with information on agricultural suitability, shared borders with conservation units and indigenous lands, native vegetation cover, land use, and pasture quality since 2008. The service provides maps of the property's current use, agricultural suitability, slope, use history, pasture history, and environmental suitability.

AgroTag MRV: a system for identifying land use and cover, collecting data in the field and integrating thematic information.

SatVeg: a tool for visualizing temporal profiles of vegetation indices (NDVI and EVI), used to support land management and to monitor the dynamics of land cover.

GHG Protocol para Agricultura e Pecuária (GHG Protocol for Agriculture and Livestock):

a tool for calculating GHG emissions, measuring emissions and removals on rural properties.

The measurement and monitoring processes fundamentally depend on how the information is collected (Figure 5.8). In general, input data can be grouped into two categories: local and remote. Local data includes soil samples, forms, and data provided by agents responsible for implementing the projects (producers or consultants), and georeferenced photographs taken on the property, among other information collected in the field. For remote data, broader sources of information originally generated for other purposes are used, such as socioeconomic data collected by public research institutes (for example, the Brazilian Institute of Geography and Statistics' Pesquisa Agrícola e Pecuária Municipal [Municipal Agricultural and Livestock Survey]), environmental data made available by the Brazilian Forestry Service based on the Rural Environmental Registry (CAR), and satellite image repositories. This combination of sources

makes for a robust and adaptable MRV system, which is key to meeting demands for traceability, sustainability, and transparency in agricultural production chains.

Future prospects

This chapter presents solutions aimed at strengthening research and innovation, production systems and agricultural practices that promote low carbon (C) emissions, as well as cutting-edge technologies that help control and manage greenhouse gas (GHG) emissions and the C balance.

Brazilian agricultural research is moving towards an era of transformation, in which innovation, integration, and sustainability are gaining strength as pillars for the development of resilient, low C emission production systems.

Advances in the study of the C balance, combined with the development of accurate measurement and monitoring methods, are essential to improve estimates of C emissions and removals and to guide strategic decisions in agricultural management. Protocols aligned with international standards and artificial intelligence tools permit real-time adjustments to management practices, optimizing C sequestration and reducing the C footprint of production systems.

There is a growing tendency in the development of technologies to combine economic and environmental gains. Complex production systems, such as integrated crop-livestock-forestry (ICLF), show that synergy between agricultural, livestock and forestry activities boosts productivity and reduces environmental impacts. Practices such as no-till farming, crop rotation, and the strategic use of legumes contribute to soil health and lower GHG emissions, promoting multifunctional landscapes that combine production, biodiversity, and C sequestration.

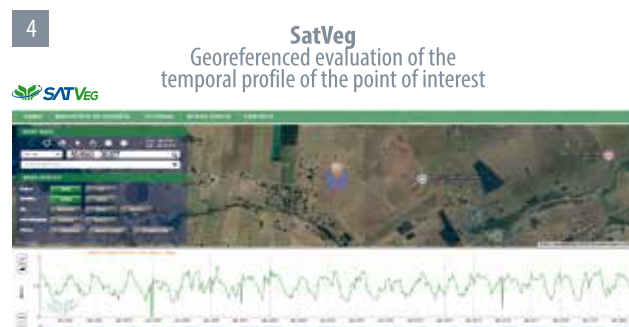


Figure 5.8. Recommended tools for applying the MRV protocol. 1. SACIR; 2. Agrotag MRV and its web interface; 3. GHG Protocol for Agriculture and Livestock; 4. SatVeg - Georeferenced evaluation of the time profile of the point of interest.

Technological innovation also stands out in the search for alternatives to nitrogen fertilization. The development of more efficient fertilizers, such as urease inhibitors, modified urea, or organomineral products, is an irreversible trend in reducing nitrogen (N) losses and direct and indirect N₂O emissions. Besides improving crop yields, this aspect makes significant contributions to mitigating environmental impacts, transforming energy liabilities into sustainable solutions.

Another emerging frontier in agricultural research is the use of bioinputs and technologies based on microbes, such as inoculants and growth promoting bacteria. The efficiency of biological N fixation (BNF), a practice that is already firmly established in soybean cultivation, points to a future where the conscious use of bioinputs can drastically reduce dependence on synthetic fertilizers, promoting a more sustainable production cycle with less environmental impact. Research indicates significant gains in both productivity and mitigation of GHG emissions by reducing the use of industrial inputs. This trend, combined with the development of innovative products resulting from collaborative efforts between academia, research institutes, and the private sector, will broaden the range of technologies available for low C agriculture.

Technologies such as biochar offer alternatives for improving soil fertility and health and sequestering C in the long term, especially in degraded areas. These innovations can transform production, promoting a “second Green Revolution” that combines productivity, sustainability, and innovation.

Measurement, reporting and verification (MRV) protocols, combined with satellite images, remote sensors, and digital platforms, strengthen transparency and efficiency in environmental monitoring and management. This integration favors the financial valuation of sustainable practices, such as certifications and C credits, and supports participation in C markets.

The convergence between innovation, sustainability, and modernization is not restricted to individual technologies, but also encompasses a paradigm shift in the way agricultural production is thought about and managed. Future research should emphasize the importance of interdisciplinary efforts, encouraging collaboration between government bodies, research institutions, and the productive sector. This collaborative dynamic will facilitate the adaptation of emerging technologies to the specific conditions in Brazil's different biomes, promoting customized solutions that meet local and regional needs. Technical training for farmers, development of incentive policies, and promotion of public-private partnerships are indispensable strategies for this transformation to take place widely and effectively.

It is impossible to ignore the challenges posed by climate change, which require a cohesive response in terms of research, innovation, and adaptation. Climate change directly affects water availability, soil health, and agricultural productivity, intensifying the urgent need to develop resilient production systems. In this scenario, technologies that permit integrated management of natural resources in real time, combined with conservation practices and the regeneration of ecosystems, are gaining prominence. Agricultural research must consequently focus not only on increasing productivity, but also guaranteeing food and (bio)energy security, in a more sustainable environment that is prepared for future challenges.

In short, the future for agricultural research in Brazil is shaped by the combination of multiple fronts: developing precise methods to measure the C balance; incorporating innovative technologies, such as more efficient fertilizers, bioinputs, biochar, and adapted cultivars; adopting biodiverse and integrated production systems; and expanding the use

of digital tools for environmental monitoring and management. This new approach, which combines technological innovation, ecological sustainability, and integrated data management, promises to transform Brazilian agriculture into a resilient, efficient, and environmentally responsible production model. At the same time, it paves the way for the country to fulfill its international commitments related to climate change mitigation and consolidate its position as a leading player in the development of low C technologies for global agriculture, with a focus on the Southern Hemisphere and tropical and subtropical regions.

Finally, this transformation requires the integration of traditional knowledge and new technologies, continuous training for producers, formulation of efficient public policies, and consolidation of a robust infrastructure for experimentation, data collection, and analysis. In this way, the agricultural sector will be able to boost its competitiveness, preserve natural resources, and guarantee sustainable agricultural development for future generations.

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Sustainable agriculture in the Amazon

How **agroforestry systems** help protect the environment¹

Even in an imposing region like the Amazon, the power of vegetation can sometimes be diminished when the land is tired or what many would consider lifeless. For years, slash and burn farming have turned vast areas into impoverished soils, where little could grow sustainably. In the small town of Castanhal, Pará, a farmer named Francisco Gomes was able to change this reality and also demonstrate that it can be reversed.

With support from Embrapa researchers, Francisco took a leading role in an innovative initiative to restore degraded areas. In 2023, his property was chosen for a pioneering experiment in the region called the Unidade de Referência Tecnológica (Technological Reference Unit, URT). The idea was to replace some often destructive agricultural practices with agroforestry systems, where different plants live together harmoniously and help restore the soil.

The land was divided into four areas, each testing a different arrangement of crops. In the first module, the açaí (*Euterpe oleracea*) cultivar BRS Pai D'égua was planted next to the cupuaçu (*Theobroma grandiflorum*) cultivar BRS Carimbó. In the second area, açaí palms shared space with cocoa trees (*Theobroma cacao*), including different genotypes of this fruit. The third module combined taperebá (*Spondias mombin*) with cupuaçu trees, and in the fourth, bacuri (*Platonia insignis*) grew alongside cocoa. The idea was to see how these plants interacted with each other, and which combinations would best help the soil recover and produce sustainable crops.

The results did not take long to appear, and as the trees grew strong and the soil showed signs of regeneration, the URT caught the attention of other producers and experts. Over 300 people visited the property, including farmers, researchers, trade unions, and government representatives. This initiative showed that it is possible to produce without

destroying, replacing the slash and burn system with something more balanced and sustainable.

Along with environmental recovery, the experience at Agrovila Iracema taught us another fundamental lesson: the importance of listening to producers. Technical knowledge from scientists was essential, but insights from Francisco and other farmers were equally valuable for this knowledge to be adapted and adopted by producers. They helped choose which species to plant, and adjusted the strategies according to the needs of the community. This exchange of knowledge made all the difference for the success of this project.

Inspired by the good results, other farmers in the region began testing agroforestry systems on their own land. In 2024 and 2025, new degraded areas began to be restored, providing benefits to both the environment and the local economy.

The Agrovila Iracema project is now a reference, proving that innovation and tradition can go hand in hand. It also shows that collaboration between researchers and farmers can transform realities and pave the way for a more sustainable future in the Amazon.



Francisco Gomes, with a 4-month-old taperebá tree, October 7, 2023.

¹ Projeto Sistemas agroflorestais de arranjos múltiplos para mitigação de mudanças climáticas na Amazônia: Unidade de Referência Tecnológica Agrovila Iracema no Nordeste Paraense (Project involving multiple-arrangement agroforestry systems for climate change mitigation in the Amazon: the Agrovila Iracema Technological Reference Unit in Northeastern Pará state), developed by Fabrício Nascimento Ferreira, Rafael Moysés Alves, Adriano Venturieri of Embrapa Eastern Amazon and Eufra Ferreira do Amaral of Embrapa Acre, with support from the Inter-American Development Bank.



Photo: Gabriel Rezende Faria (Embrapa)

CHAPTER 6

Carbon accounting and life cycle assessment for Brazilian agricultural products

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Introduction

Responding to climate change involves identifying and quantifying the emissions that cause this impact, which can be done using different approaches. Given the critical and urgent nature of this problem, accurate metrics are crucial. In order to determine the potential environmental impacts of products, life cycle assessment (LCA) is one of the most internationally recognized quantitative methodologies, with a strong scientific foundation. When dealing specifically with climate change, this metric¹ is known as the carbon footprint of products; when it refers to impacts on water consumption and quality, it is called the water footprint.

LCA studies began at Embrapa in the early 2000s. Initial research on this topic focused on the main Brazilian commodities, especially those destined for export or energy use (such as sugar cane, soybeans, corn, oil palm, etc.), and tropical fruit, products with higher added value that are shipped to markets which are demanding in terms of environmental issues (including cashews, coconuts, mangoes, melons, and derived products). These studies generated inventories for

¹ Life cycle assessment is a quantitative methodology based on mass and energy balances in the transformation and transportation processes within a product's life cycle; in other words, it consists of applying a metric.

agricultural processes which were published in national and international databases, along with the environmental profile of the resulting products. At the same time, Embrapa was creating an important model for analyzing land use changes. These initiatives contributed to the greater representativeness and commercial competitiveness of Brazilian agricultural products.

With regard to energy crops, the work has evolved into contributions to public policies, such as the Política Nacional de Biocombustíveis (National Biofuels Policy, RenovaBio), and international policies like the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the standards of the International Maritime Organization (IMO), a specialized agency of the United Nations (UN) responsible for regulating international maritime transport. Work on tropical fruit, on the other hand, has focused on carbon footprint and water footprint analysis, as well as important modeling studies for biorefineries. This research is intended to use fruit in its entirety by developing economically and environmentally sustainable technological routes to extract compounds from peels and pits, such as starch extracted from mango pits and nanocellulose extracted from the fibers of green coconut shells and sugarcane bagasse.

New initiatives have emerged with the use of LCA in the dairy and beef cattle production chains, mainly in carbon footprint studies, as well as in important crops adapted to the subtropical climate and the Cerrado biome, such as wheat. Also noteworthy is recent research involving the creation of tools to support Embrapa's low-carbon programs dedicated to soybeans, corn, sorghum and wheat, as well as dairy and beef cattle.

This chapter will first present the current panorama of the LCA methodology and challenges related to its application in tropical agriculture, followed by some innovation

solutions generated by Embrapa and its partners that integrate knowledge and technologies on this topic.

Current panorama

What is life cycle assessment?

Life cycle assessment (LCA) is an environmental management tool that makes it possible to evaluate the environmental performance of products and services. Using a systemic approach, "cradle to grave" LCA quantifies potential environmental impacts considering the entire life cycle, from the extraction of raw materials to production, distribution, use, and final disposal of a product.

In addition to identifying the stages of the life cycle that contribute most to impact generation, the results of the LCA make it possible to propose improvements, integrate environmental aspects into projects and development processes, compare technological pathways and products with similar functions, and provide support for environmental declarations. This methodology has a strong scientific foundation and is internationally recognized and standardized through several norms, including ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization, 2006a, 2006b). In addition to these general standards, there are also specific versions that focus on certain impacts, such as ISO 14067 (International Organization for Standardization, 2018), which details the steps for studying the carbon footprint, and ISO 14046 (International Organization for Standardization, 2014), which guides analysis of a product's water footprint. Note that when the assessment of the water footprint is focused on water scarcity, it is referred to as the water scarcity footprint.

LCA studies are carried out for different scopes and applications, in academia as well as the

manufacturing and government sectors. Because of their inherent complexity, these studies challenge scientific research to develop technological solutions to enable their proper use. In this sense, Embrapa's contributions include environmental models, process models, and tools for building life cycle inventories to estimate the carbon footprint and the environmental profile of agricultural products.

Life cycle assessment in the tropical agricultural environment

LCA is a methodology originally proposed for industrial processes. This technique involves accounting the material and energy flows exchanged between the place where production processes occurs and the environment, and assumes closure of mass balances. In a physically limited structure (like manufacturing settings), these flows can be controlled. Atmospheric emissions, liquid effluents, and solid waste must be treated and reported in accordance with environmental legislation.

Agricultural processes² take place in the open, with no physical boundaries between the production space and the natural environment. For this reason, many outflows are not quantifiable but instead are estimated by models, and depend on specific parameters of climate, soil, plant characteristics, and aspects related to nutritional and plant health management.

Models for estimating outflows from production systems into environmental compartments are presented in methodological guides for LCA studies, generally associated with life cycle inventory (LCI) databases (Nemecek; Kägi, 2007; Nemecek et al., 2001; Nemecek; Schnetzer, 2011; Calvo Buendía et al., 2019; Van Paassen et al., 2019; Koch; Salou, 2020). These guides bring together

models originally developed for temperate climate agriculture, which require adaptation or parameterization to better represent agriculture in tropical and subtropical climates (Matsuura; Picoli, 2019). One of the solutions presented in this chapter is the BR-Calc tool, a component of ICVCalc, which is used to generate inventories of agricultural processes based on models and factors adapted to Brazilian agriculture.

Unlike temperate regions, in regions with a tropical climate more than one crop can be grown during the same agricultural year, either in sequence (harvest, second crop, second harvest, third harvest, etc.) or in an integrated manner (Hirakuri et al., 2012). Better use of the agricultural area is one benefit of adopting more complex systems, which also offers other advantages such as sharing natural and technological resources, as well as the impacts generated by their use. Attribution of environmental impacts to the products of a production system³ is commonly done by allocation,⁴ using a physical criterion (such as mass, volume, energy, exergy,⁵ or occupation time) or economic criteria. ICVCalc adopts an allocation model that distributes the impact factors among the commercial products derived from a production system, simultaneously considering the area and occupation time of each land use (commercial

² In this text, agricultural processes are understood in the broad sense, and include forest and livestock processes as well as systems that integrate them.

³ A “[...] production system is composed of the set of crop and/or livestock systems within a rural property, defined based on production factors (land, capital and labor) and interconnected by a management process” (Hirakuri et al., 2012, p. 13, translation ours).

⁴ Allocation is defined as the “partitioning the input or output flows of a process or product system between the product system under study and one or more other product systems” (International Organization for Standardization, 2006a, p. 4).

⁵ Exergy is the portion of a system's energy that can be converted into useful work when the system is brought into thermodynamic equilibrium with its reference environment, taking into account the temperature, pressure, and chemical composition of the medium.

crops and service activities⁶) in a complete production cycle. This criterion (area and time of land occupation combined) was selected because the shared resources pertain to the agricultural land resource: land occupation and greenhouse gas (GHG) emissions derived from land use change and liming (through the burning of vehicle fuels as well as the use of lime itself as an input). Because the choice of allocation method significantly affects the outcome of the LCA, a sensitivity analysis is recommended in order to determine the consequences of this choice (The European Feed Manufacturers' Federation, 2024).

Within this context, some production chains that are significant to the Brazilian economy (for national supply as well as exports) have expressed interest in using LCA as a tool for analysis and decision making, with a view to reducing GHG emissions, water scarcity, and other environmental impacts. The current panorama in some of these chains is described below.

Life cycle assessment for meat and milk

Embrapa is taking part in global efforts to develop technologies that help increase production efficiency and mitigate GHG emissions in livestock farming, meeting the expectations of a society with consumers who demand less environmental impact from production.

When discussing GHG emission reduction in livestock farming, it is essential to consider the most appropriate metrics; one of the most internationally recognized and easily understood metrics is emission intensity, which represents how much of these gases have been emitted. This emission intensity, when calculated according to

LCA assumptions and related to a given quantity of product, is called the carbon footprint.

In order to reduce the carbon footprint of animal products, there are three potential lines of action: first is to manipulate rumen fermentation, using additives, grains, improved pastures, and more digestible diets. These technologies contribute to a more favorable fermentation pathway for the animal, with lower methane production. The second line of action is to improve the efficiency of the production system using widely available technologies related to animal health, nutrition, reproduction, and management of the production chain. The third line of action is related to GHG removals,⁷ including carbon sequestration,⁸ which can occur in both well-managed pasture and agricultural soils, as well as the trunks and roots of the tree component of integrated crop-livestock-forestry (ICLF) systems.

The mitigation objectives of the first two lines of action are often achieved by technologies such as the use of supplements for grazing animals, or intensification of grazing⁹ in well-managed

⁷ According to the IPCC's AR6 WGIII (Shukla; Skea, 2022, p. 36), greenhouse gas removal refers to human activities that remove GHGs from the atmosphere and store them in geological, terrestrial, or ocean reservoirs, or in products. Removal includes carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) or other GHGs, as well as processes such as DAC (direct air capture), BECCS (bioenergy with carbon capture and storage), reforestation, and increasing soil carbon.

⁸ Carbon sequestration is the process of storing carbon in a reservoir (or carbon "pool"), such as forests, soils, geological formations, or oceans, so that it remains out of the atmosphere for a sufficiently long time ("on climatically significant timescales") to reduce atmospheric carbon dioxide (CO₂) concentrations and consequently mitigate climate change. (IPCC, 2025).

⁹ "Grazing intensification" refers to boosting the efficiency of pasture use by animals, through herd management and forage utilization strategy. It relates to management of the grazing process itself, in other words, how, how much, when, and for how long the animals graze a given area.

⁶ Service activities include green manure, cover crops, fallow land, etc.

areas. Congio et al. (2021) analyzed 130 scientific studies conducted in Latin America and the Caribbean that quantified the impacts of different methane mitigation strategies. These authors found that the most efficient strategy was genetic improvement in animals (leading to a 38% reduction), followed by proper pasture management (22–35%), and finally improving the animals' diet by including higher levels of protein and concentrated feed (10–20%). The impacts of supplementation and confinement were studied by Méo Filho et al. (2020), who pointed out that these technologies have expanded as a viable alternative, more efficiently reducing GHG emissions per kilo of weight gain, especially when associated with innovative technologies such as the use of additives that directly reduce methane emissions. Additives such as essential oils and byproducts from agroindustry, which contain secondary compounds that directly affect methane generation, have been studied by Pena-Bermudez et al. (2022), Budel et al. (2023), and Benetel et al. (2024).

With regard to pasture intensification,¹⁰ Oliveira et al. (2020) demonstrated that a larger number of animals grazing in a well-managed area had lower emissions per kilogram of product (2.0 kg CO₂eq/kg carcass), while degraded pastures resulted in carbon footprints up to 25 times higher (50.3 kg CO₂eq/kg carcass). Similarly, Méo Filho et al. (2022) observed a 50% reduction in the intensity of methane emissions when comparing intensive and extensive grazing management (6.75 versus 13.5 kg CO₂eq/kg carcass).

Grass and legume intercropping systems are also efficient alternatives for decreasing the carbon footprint, since the forage ingested has higher levels of protein and digestibility, which mitigates emissions. Legumes also fix nitrogen

biologically, reducing the need for synthetic fertilizers and promoting a positive nitrogen balance, equivalent to 150 kg/ha.year of urea, with a 23% reduction in emissions per unit of product (Homem et al., 2024). Furtado (2022) and Furtado et al. (2023) showed a 70% reduction in the intensity of methane emissions when intercropping marandu grass with pigeon peas, mainly due to the increase in weight gain during the dry season.

Carbon sequestration in pasture soils with intensified grazing was studied by Oliveira et al. (2022), who indicated values of 1.92 and 1.80 t CO₂eq/ha.year for systems without irrigation and with high and medium stocking rates, respectively. Crop-livestock-forest integration systems (ICLF), a technology that has been widely studied and disseminated by Embrapa, also deserve attention in terms of carbon sequestration in soils and tree trunks. Oliveira et al. (2024) concluded that improved land use management and the introduction of trees had a positive impact on soil carbon content. Carbon sequestration in integrated tree and pasture systems occurs in deeper layers. A double-benefit effect was observed in the increase in carbon content in shallow soils (pasture effect), and in deeper layers (eucalyptus effect). Almost half of the carbon stock at a depth of one meter is concentrated in the first 30 cm from the surface. Total carbon sequestration in soils and trunks reached 19 t CO₂eq/ha.year. Brunetti et al. (2025) pointed out that, even in an intensive system with 2.5 times more animals than the Brazilian average and providing additional feed, integrated forest-livestock systems offset 77% of enteric CH₄ emissions by fixing carbon in tree trunks, resulting in a better balance between emissions and removals (-14.28 t CO₂ eq/ha.year).

Complementary studies involving integrated production systems to mitigate GHG emissions have also shown that these systems are more efficient in terms of water use, helping to

¹⁰ Pasture intensification is a set of strategies and management practices to increase livestock productivity per hectare, through improvements in pasture conditions, use of inputs, and herd management.

reduce the water footprint¹¹ of Brazilian beef. Systems that integrate crops and livestock (ICL) and crops, livestock and forests (ICLF) have the potential to reduce freshwater consumption when raising beef cattle on pasture, improving forage use efficiency and reducing forage evapotranspiration (Barsotti et al., 2022), with positive effects on feed conversion efficiency and water productivity compared to extensive systems involving monospecies pastures (Barsotti et al., 2024). Barsotti et al. (2025) also observed that green water scarcity is low in agropastoral systems (182 to 328 L/kg of carcass weight), and that integrated systems reduce the water footprint of beef cattle by up to 69%, making them efficient strategies for reducing the environmental impacts of water consumption in pasture-based livestock systems. After 14 years, the same ICLF and ICL systems exhibited carbon stocks in the 0–20 cm soil layer of 3.2 and 7.4 Mg/ha, respectively, and carbon accumulation rates of 231.7 and 531.4 kg/ha.year, respectively (Almeida et al., 2023).

These technologies, with effects that have been tested in field experiments, can be used to calibrate and validate mathematical models for estimating emissions while also serving as input data for carbon footprint calculators. Adjustments and calibrations in models to define parameters suitable for the tropical environment (“tropicalization”) are necessary so that they reflect Brazilian production conditions. Developing protocols and tools to calculate the GHG balance and incorporating good

practices to improve this balance generate relevant information for decision making on investments, technologies, and processes used in rural enterprises that are capable of reducing the carbon footprint attributed to animal products.

Life cycle assessment applied to the study of the carbon and water footprints of tropical fruits

Fruit farming stands out due to the value of production, the number of jobs generated per cultivated area, which according to Sobel and Costa (2004) ranges from 0.8 to 1.2 direct jobs per cultivated hectare, the inclusion of women in the job market, especially in the post-harvest phase, as well as its role in leveraging the service sector. In comparison, soybean cultivation is a highly mechanized and large-scale crop that generates few direct jobs per hectare. Studies like those by the Companhia Nacional de Abastecimento (Brazilian National Supply Company, or CONAB) (Conab, 2025a), and researchers such as Graziano da Silva (2004) and, more recently, Barcellos et al. (2017), indicate that soybean generates around 0.05 to 0.07 direct jobs per hectare cultivated. In regions with a high level of mechanization, such as MATOPIBA (an area spanning parts of Maranhão, Tocantins, Piauí and Bahia) or the Midwest, this figure can drop even further, to 0.03–0.04 jobs per hectare).

Brazil ranks third worldwide in fruit production, behind only China and India, with most of its production (98%) supplying the domestic market. Notable among these products in 2024 were:

- Bananas (7,046,345 tons; 469,989 hectares planted; gross production value of R\$ 16,062,591,000).
- Coconuts (2,105,345,000 units of fruit; R\$ 2,275,451,000).
- Guavas (557,225 tons; R\$ 1,385,628,000).

¹¹ The water footprint method with color classification (namely blue, green, and gray water) was proposed by the researcher Arjen Y. Hoekstra, one of the founders of the modern water footprint concept and the Water Footprint Assessment Methodology. The colors are defined in this method as follows: blue water is surface or groundwater used (rivers, lakes, aquifers); green water is rainwater stored in the soil and used by plants (evapotranspiration); and gray water is the volume of water needed to dilute pollutants to acceptable levels (Hoekstra et al., 2011).

- Cashew apples (159,212 tons of nuts; 819,000 liters of cajuína beverage derived from the fruit; 441,892 ha; R\$ 689,335,000).

In terms of foreign market, according to IBGE (2025) and MAPA (2025), the leading exported from Brazil in 2023 were:

- Mangoes (266,000 tons; 80,465 ha; US\$ 284.89 million).
- Melons (228,000 tons; 30,535 ha; US\$ 183.11 million).
- Grapes (73,000 tons, 77,019 ha; US\$ 172.01 million).

Numerous studies (shown in Figure 6.1) have assessed the carbon footprint of tropical fruits such as melons, mangoes, bananas, and green coconuts. A comparison of different studies showed that mangoes, in a system incorporating green manure (“plant cocktail”), were the only fruit with a negative carbon footprint (in other words, because of the use of the plant cocktail between the rows, the carbon stock in the biomass and soil was greater than the emissions during the product’s life cycle). Considering the average of several studies with fruits around the world, it was estimated that the footprint of a fruit leaving the farm is 0.5 kg CO₂ eq/kg, varying ± 0.36 kg CO₂ eq/kg (Subedi et al., 2024). It is important to note that although the equations and factors for estimating emissions from the Intergovernmental Panel on Climate Change (IPCC) were used in these studies, both the factors and the global warming potential (GWP) varied with the evolution of climate science over time. Furthermore, emissions from Land Use Change (LUC), seedling production, packaging, and transportation of the fruit to the consumer market were disregarded in most studies. In the cultivation of perennials (such as cashew, mango, and green coconut), few studies have covered all phases of the orchard (establishment, growth, and full production).

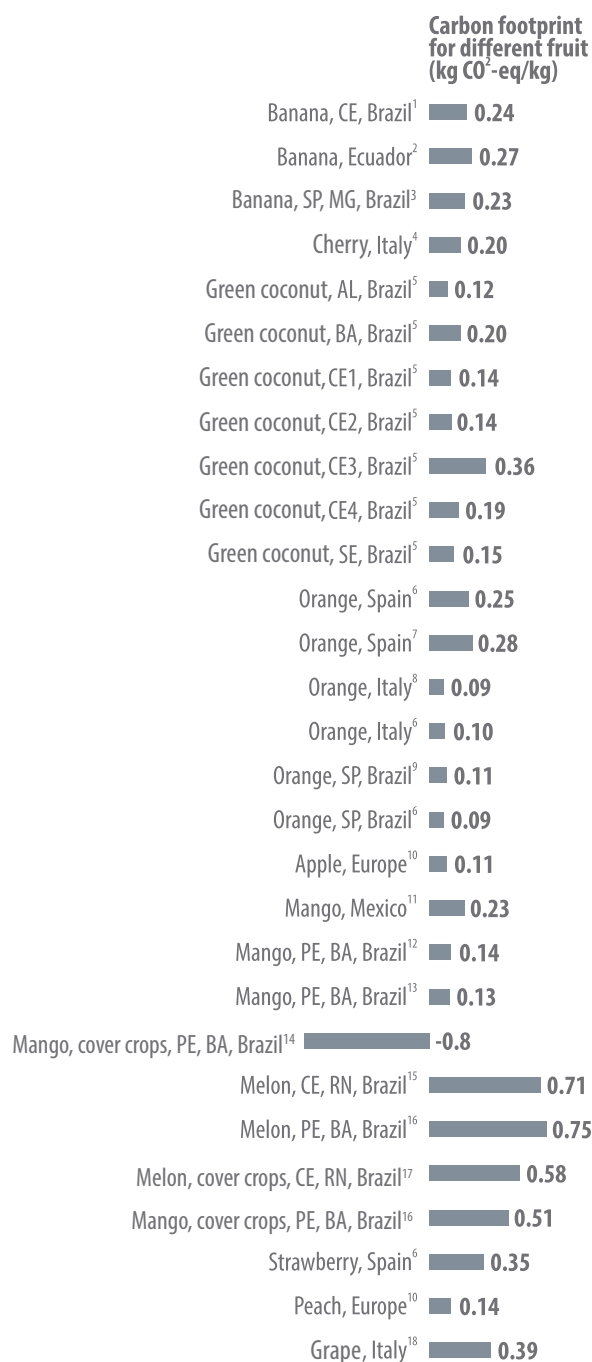
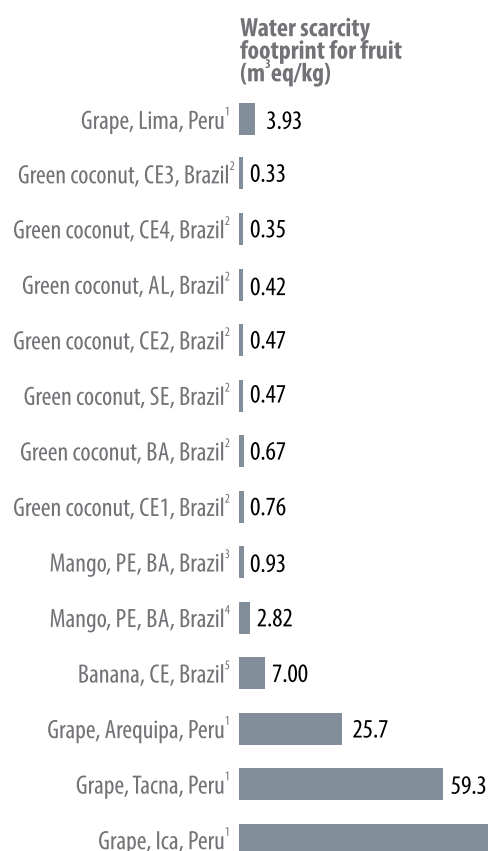


Figure 6.1. Comparison of the carbon footprint for different fruits produced in different countries and reported in various studies.

Note: These studies differed in the scope and year of the GHG emission and GWP factors.

Source: ¹Lima et al. (2024), ²Roibás et al. (2016), ³Coltro e Karaski (2019), ⁴Tassieli et al. (2018), ⁵Sampaio et al. (2021), ⁶Mordini et al. (2009), ⁷Ribal et al. (2019), ⁸Giudice et al. (2013), ⁹Knudsen et al. (2011), ¹⁰Vinyes et al. (2017), ¹¹NMB (2010), ¹²Basset-Mens et al. (2016), ¹³Muller-Carneiro et al. (2018), ¹⁴Dias et al. (2020), ¹⁵Figueirêdo et al. (2013), ¹⁶Santos et al. (2018), ¹⁷Barros et al. (2019), ¹⁸Marras et al. (2015).

Analyses of the water scarcity footprint of fruits are less frequent than investigations of the carbon footprint, and use different assessment methods. Studies that adopted the Aware (Available Water REmaining) method, recommended by the Life Cycle Initiative (Boulay et al., 2016), which used annual scarcity indices generated by Boulay et al. (2018), show significant contrasts. Irrigated grape production in Peru, in watersheds with an arid climate, had the highest water footprint, while green coconuts grown in Ceará had the lowest (Figure 6.2). It should be noted that in the research on grapes, the water scarcity footprint varied widely (from 3.93 to 208.4 m³-eq/kg) according to the location of irrigated production in the different river basins in Peru (Vázquez-Rowe et al., 2017).



Life cycle assessment for wheat

Production of wheat and derived products, such as flour, pasta, cookies, and bread, is of vital importance to the global diet. Around the world, wheat accounts for around 18% of calories and 19% of protein ingested daily (Mottaleb; Govindan, 2023). Together with rice, corn, and sugar cane, wheat accounts for almost half of the world's annual agricultural production in terms of tons produced (Food and Agriculture Organization of the United Nations, 2025). Although the volumes produced and consumed are key factors in understanding a product's relevance to climate issues, it is necessary to understand how it is produced and how the product reaches the consumer.

The LCA of wheat and wheat flour was pioneered in Brazil and Latin America, as reported by Giongo et al. (2025).

The integration of sustainability parameters into the requirements that companies demand of their suppliers is not new (Amini; Bienstock, 2014; Beske et al., 2014). Production that uses inputs with a lower environmental impact is increasingly part of corporate strategies and commitments between the productive sector and its stakeholders. For this reason, it is essential for organizations that buy and use wheat and its derivatives to understand how these products are produced and what their impacts are, so that there are no interruptions in production, supply,

Figure 6.2. Comparison of the water scarcity footprint of different fruits produced in different countries and reported in various studies.

Note: The scope of these studies ranged from input production and transportation to agricultural production areas. Only the mango study considered the post-harvest and packaging stages for this fruit.

Source: ¹Vázquez-Rowe et al. (2017), ²Sampaio et al. (2021), ³Muller-Carneiro et al. (2019), ⁴Dias et al. (2020) e ⁵Lima et al. (2024).

or trust. In this way, multidimensional criteria for sustainability (social, environmental, and governance) can be implemented in transactions within the value chain. These parameters need to be managed so that they do not increase the transaction costs involved (Dossa et al., 2023), and must take into account various uncertainties. One of the ways to reduce this problem is to increase the accuracy of measurements and rigor in the control of criteria such as the carbon footprint.

Lack of carbon footprint metrics for specific producing regions is a problem. Production systems are adapted to the various characteristics of an area, such as climate, soil, land structure, and marketing logistics (Giongo et al., 2025). For this reason, applying the carbon footprint of a region with a different production system creates uncertainty about the validity of this data. This shows that environmental impact estimates (including those related to climate change) should be as close as possible to the production system that generated the product under analysis. For Brazilian wheat cultivation, this is especially relevant.

Wheat production in Brazil is classified into four regions — cold and humid, moderately hot and humid, moderately hot and dry, and hot and dry — defined to guide the adaptation of cultivars while taking into account criteria such as water regime, temperature and altitude (Reunião da Comissão Brasileira de Pesquisa de Trigo e Triticale, 2023). Following the criteria for agricultural climate risk zoning (ZARC), the areas colored blue, yellow, green, and orange in the image below indicate regions suitable for recommended wheat cultivars. The area in red corresponds to regions where wheat cultivation is not recommended, due to adverse climatic and soil conditions. Areas within states without colors represent regions that are excluded due to agroclimatic restrictions. The first three regions (blue, yellow, and green) are spread across the southern states of Brazil, as well

as southern São Paulo and parts of Mato Grosso do Sul. The last region (orange) is located mainly in the Brazilian Cerrado, and characterizes tropical wheat (Figure 6.3).

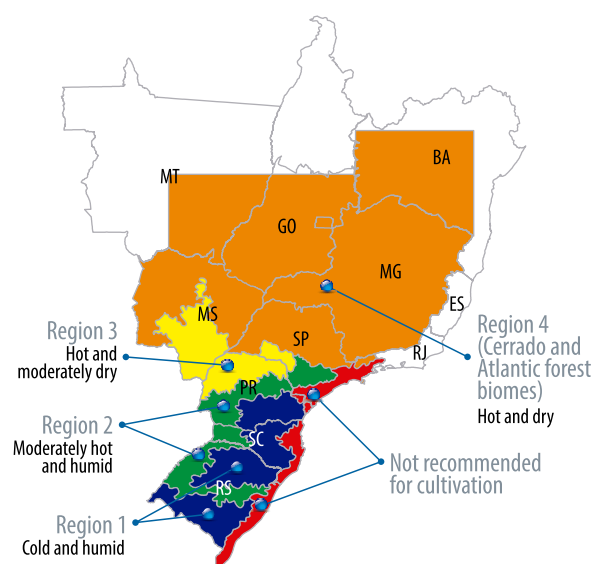


Figure 6.3. Homogeneous adaptation regions for wheat cultivars in Brazil.

Source: Pasinato et al. (2018).

Wheat production in Brazil has grown significantly in recent decades (Figure 6.4), from just 3.2 million tons to more than 8.4 million tons (estimated) in just 25 years. Production reached record levels in 2022 with 10.5 million tons, almost matching the country's annual demand of around 12.5 million tons (Associação Brasileira da Indústria do Trigo, 2022). This production is mainly concentrated in Brazil's three southern states, which accounted for an average of 87.8% of national production over the past five years (Conab, 2005b). Even so, we must highlight the growth in wheat production in the fourth homogeneous region for adapting cultivars, the Cerrado and Atlantic Forest (Figure 6.3).

The significant growth in wheat production in Brazil is closely linked to increased productivity. Over the past 25 years, productivity has grown

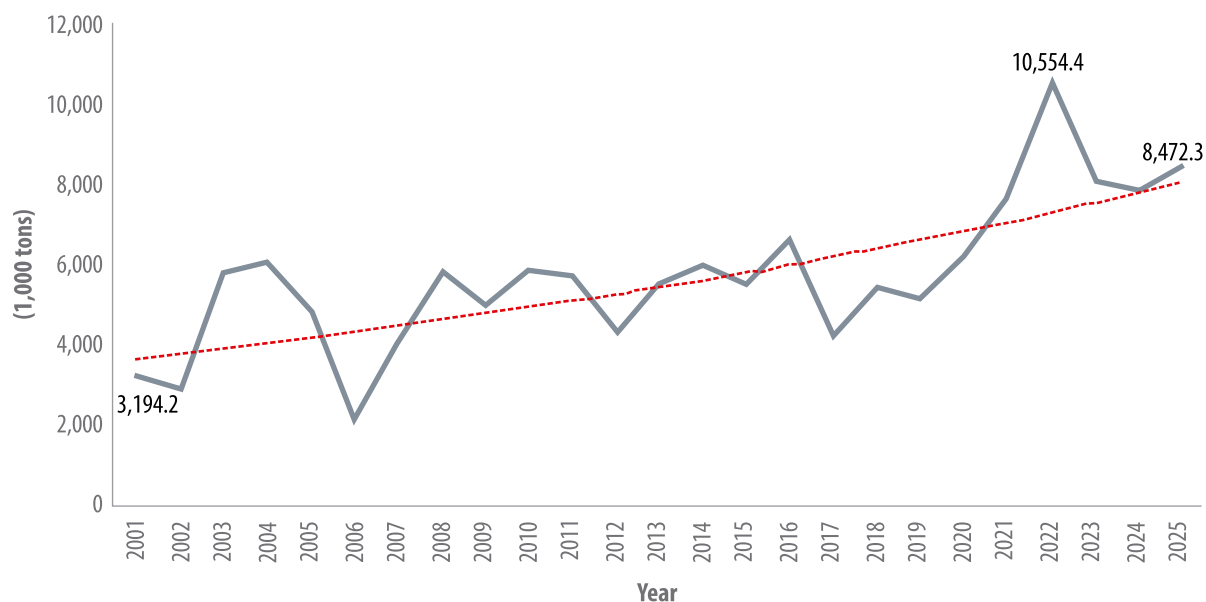


Figure 6.4. Wheat production in Brazil from 2001 to 2025 (in thousands of tons).

Source: Conab (2005b).

by approximately 64%, as shown by CONAB data (2025b), from around 1.8 t/ha in 2001 to 3.0 t/ha (estimated for the 2025 harvest). The remainder of this increase in production resulted from the expansion in cultivated area (Figure 6.4).

In this sense, it should be noted that wheat growing does not promote the clearing of new areas. Wheat is rotated with other temporary crops (such as soybeans, corn and beans), increasing land use efficiency and reducing fallow areas and monoculture farming that damages the soil (Denardin et al., 2019).

Brazilian wheat cultivation is currently evolving in a significant manner, most notably due to large-scale adoption of innovations such as drones and bioinputs (Compre Rural, 2023), the expansion of wheat in the Cerrado region (Chagas et al., 2021; Acosta, 2018), and growing multi-institutional concern with reducing environmental impacts (Dossa et al., 2023). Among these advances, the growth of tropical wheat deserves special attention. The expansion of wheat into Brazil's Cerrado region is part of a broad, coordinated

multi-stakeholder effort to achieve self-sufficiency in domestic wheat production. Previous work (Acosta, 2018; Acosta; Ramos, 2021; Farias et al., 2024) has shown the potential for increasing wheat production in Brazil based on different models, by either increasing productivity or expanding the planted area in regions that are already consolidated agricultural areas, as is the case with tropical wheat.

This is important when analyzing the possible impacts of such an increase in production. According to data from the Ministério do Desenvolvimento, Indústria, Comércio e Serviços (Ministry of Development, Industry, Trade and Services, MDIC), between 2015 and 2024 Brazil imported 11.3 billion dollars' worth of wheat to meet domestic demand. For this reason, increasing our own wheat production capacity addresses multiple dimensions of sustainability: bringing production geographically closer to consumption, reducing foreign dependence on a staple food, reducing foreign spending, improving the trade balance, and finally, encouraging crop rotation and soil protection.

Interviews with experts from the region indicate that wheat production in the Brazilian Cerrado can be grouped into two categories: rainfed wheat and irrigated wheat. Irrigated wheat production has greater productivity potential, reaching averages of 6 tons per hectare. While rainfed production has lower productivity (around 2 to 2.5 tons per hectare), it has a larger area for expansion, considering the presence of soybeans and corn that are already established in the region. Irrigation for wheat is uncommon in the traditional growing region (South), except in specific situations such as seed production. This demonstrates different potential environmental impacts (water and carbon footprint), which increases the need for geographically localized assessment of these production systems. It is consequently necessary to coordinate actions through a program that focuses on this issue.

With the challenge of producing all the wheat Brazil needs and promoting global food security, the Programa Trigo Baixo Carbono (Low-Carbon Wheat Program) (Dossa et al., 2023) incorporates climate change adaptation and mitigation strategies into its scope, using LCA as a tool to assess challenges and opportunities for continuous improvement in the wheat chain. The study by Giongo et al. (2025) presents the carbon footprint of wheat produced in the south of the country as one of the first initiatives to report on the environmental performance of this Brazilian product. Despite advances in applying LCA to crops such as wheat, there is still a lack of representative studies on wheat production in the Brazilian Cerrado. This gap reinforces the importance of expanding LCA studies to other tropical biomes and agricultural systems.

Innovation solutions

Based on the current panorama presented above, with regard to LCA itself and the calculators adapted to the tropical environment

as well as their use in production chains that are important for the national economy, the innovation solutions presented below were developed by Embrapa and its partners as part of efforts to improve the technical, economic, and environmental efficiency of Brazilian agricultural products.

Methods for estimating land use change and greenhouse gas emissions

Land use change (LUC) is one of the processes with the greatest potential impact on the carbon footprint of agricultural products. Land use change can increase greenhouse gas (GHG) emissions by 8 to 20 times compared to emissions from all other processes involved in agricultural production (Castanheira; Freire, 2013; Poore; Nemecek, 2018). The process is also very relevant for other impact categories, such as biodiversity and ecosystem services (Defries et al., 2004; Calvo Buendía et al., 2019). In Brazil, land use change has been responsible for a considerable share of national GHG emissions, contributing an average of 43% of the country's total net emissions during the 2002–2022 period (Brasil, 2022). Accurate estimates of land use change are consequently critical for carbon footprint and LCA studies of Brazilian products and, in turn, activities to decarbonize production chains.

Land use change can be direct or indirect (International Organization for Standardization, 2018). Direct change (direct LUC or DLUC) occurs when there is a change in land use within the boundaries of the system, while indirect change (indirect LUC or ILUC) occurs outside the boundaries of the system, caused by a direct change (International Organization for Standardization, 2018). For example, when a study focuses on crop X, and the system under analysis is the farm used for that crop, the change in land use from pasture to crop X within the

farm is a DLUC. Meanwhile, the expansion of this displaced pasture over an area of forest on the neighboring farm, or in the neighboring country, can be considered an ILUC.

The accounting of GHG emissions derived from DLUC is often required in international carbon footprint protocols and standards, such as the ISO standard (International Organization for Standardization, 2018) and the GHG protocol (Greenhouse Gas Protocol, 2022). However, collecting primary data for this task can be costly, laborious, or even unfeasible, because high-resolution data is lacking or due to the high costs and time involved (Brenton et al., 2021). To overcome this limitation, methods and tools have been developed internationally to make DLUC estimates available for use in carbon footprint studies (for example, in Blonk Consultants, 2021; Lam et al., 2021). In the past, however, DLUC estimates were often only available nationally (such as in Tubiello et al., 2021), or only for crops in specific regional and temporal demarcations (for example, in Figueirêdo et al., 2013; Maciel et al., 2015), or contained inconsistent representations of Brazil's territory (for example, as reported in Novaes et al., 2022).

Within this context, Embrapa has coordinated actions and projects to research and develop methods and studies that permit a more accurate estimate of land use change and GHG emissions, in order to provide support for LCA and carbon footprint studies of Brazilian agricultural products. The main lines of action include: 1) development of the Brazilian land use change (BRLUC) method for estimating DLUC for Brazilian products; 2) generating data and information to support the consideration of LUC in public policies involving carbon accounting.

The BRLUC method was developed to permit estimation of the carbon dioxide (CO₂) emissions and removals caused by land use change associated with Brazilian and sub-national agricultural products, and is compatible with

the main international protocols. Its first version estimated state emissions for 64 crops, as well as pasture and forestry (Novaes et al., 2017). An improved version provided municipal results, based on spatially specific data (Garofalo et al., 2022). Both versions are available to access and download free of charge from the Embrapa portal.¹² A new version is currently in the final stages of publication, and will provide emissions that also consider the land use management practiced in Brazil's different regions, along with estimates of municipal carbon stocks.

Because of its consistency and comprehensiveness, the results of the BRLUC method have been incorporated into one of the main international life cycle inventory databases, Ecoinvent¹³ (Donke et al., 2020). Its data has also been incorporated into the international GFLI database and the Banco Nacional de Inventários de Ciclo de Vida (National Life Cycle Inventory Database, SICV-Brasil),¹⁴ managed by the Instituto Brasileiro de Informação em Ciência e Tecnologia (Brazilian Institute of Information on Science and Technology, Ibict/MCTI). This method is also in the process of being incorporated into other databases, such as Hestia¹⁵ and the Orbae system.¹⁶ Incorporation into these databases and systems will lead to broader adoption of the method and its results by its many users, which are diverse and range from large research centers and governments to multinational consulting firms and agroindustry. This adoption will allow studies on Brazilian agricultural products to present more accurate results on the national production system.

¹² Available at: <https://brluc.cnpma.embrapa.br>

¹³ Available at: <https://ecoinvent.org/the-ecoinvent-database>

¹⁴ Available at: <https://sicv.acv.ibict.br/Node>

¹⁵ Available at: <https://www.hestia.earth>

¹⁶ Available at: <https://orbae.adastra.eco>

Some of these studies have been published, and provide a sample of the method's wide range of applications. Examples include studies on: the impact of fish feed (Silva et al., 2018); the carbon footprint of mango and sisal production in the Semi-Arid region (Folegatti-Matsuura et al., 2019; Müller Carneiro et al., 2019), of Brazilian beef (Dinato et al., 2019), of coconut in the Brazilian Northeast (Sampaio et al., 2021), and of soybeans produced in Pará (Brito et al., 2021); performance in manufacturing of jeans in Brazil (Morita et al., 2020); and the effects of modeling on the carbon footprint of biofuels (Brandão et al., 2021). This sample demonstrates the wide versatility of the method, along with its application in a wide array of settings.

Based on the experience acquired in these research and development activities, Embrapa has also contributed to more effective consideration of land use change in public policies involving carbon accounting. One central highlight has been its work with RenovaBio, which resulted in the plan to define the program's eligibility criteria (Moreira et al., 2018; Novaes et al., 2023). The team has also contributed technical notes and information for international policies, for example in defining criteria and parameters to assess sustainability in the life cycle of biofuels for use in aviation for CORSIA and for ocean shipping for IMO, as well as in the European Commission's Renewable Energy Directive (RED). It has also worked with the UN Food and Agriculture Organization (FAO) to adjust data on Brazil's agricultural area (Novaes et al., 2022), with a major impact on global land use change models.

In addition to significant contributions to the development of solutions related to land use change, Embrapa Environment and its partners have dedicated their efforts to developing computer tools for LCA and preparing inventories for agricultural processes in order to estimate the

carbon footprint of products and accessory tools like the ones presented below.

ICVCalc-Embrapa – a tool for tropical agricultural inventories

ICVCalc-Embrapa is a tool for constructing inventories of agricultural processes for LCA studies, which in turn make it possible to achieve greater accuracy in studies of the national production system. There are currently two versions: the first was developed in Microsoft Excel¹⁷ (Folegatti-Matsuura et al., 2022), and the second is available as a web system.¹⁸

The Excel version covers the main international methodological protocols used to estimate emissions from agricultural processes in the different environmental compartments: a) Nemecek (Nemecek; Schnetzer, 2011); b) WFLDB (Nemecek et al., 2015); c) Agri-footprint (Van Paassen et al., 2019); d) Agribalyse (Koch; Salou, 2020); and e) IPCC (2020). BR-Calc was developed by Embrapa Environment, by adapting models from other protocols to better represent Brazilian agricultural processes and including climate and soil databases for the country's mesoregions.

The tool has two options for entering data: raw data or previously processed data. In the first option, data related to the harvest of an agricultural crop is used, processed in the Primary Data spreadsheet. The Allocation spreadsheet is used for crops that are part of a cropping system, and is intended for calculating the allocation of environmental loads related to resources consumed and impacts generated, which must be shared between the agricultural products in that system. In the second option, flows

¹⁷ Available at: <https://www.cnpma.embrapa.br/download/icvcalc>

¹⁸ Available at: <https://icvcalc.cnpma.embrapa.br>

(resources from nature or the technosphere¹⁹) that are already normalized for one hectare or one kilogram of product are entered into the Input Data spreadsheet.

All the methodological protocols have two spreadsheets: a) Calc, for entering the technical parameters that feed the environmental models specific to each protocol; and b) LCI, which consolidates the inventory of the agricultural process, made up of all the input and output flows. Additionally, in the Excel version of ICVCalc there is the Emissions Comparison spreadsheet, which shows the emissions results for the different environmental compartments estimated in each protocol.

The ICVCalc web version is a derivation of the first tool, which specifically processes the BR-Calc model. In addition to the calculation structure, ICVCalc web is made up of several auxiliary databases and consumes APIs (application programming interfaces) from other software (such as BRLUC), which makes it easier to build inventories for agricultural processes. It was developed in Python and offers a more user-friendly interface. Data is entered by agricultural plot, and users are taken through a sequence of pages that allow them to describe their production system in detail (in this case, with no built-in allocation model). The result is an inventory for the agricultural process (as in the Excel version), but in a format that is compatible with the main LCA support software. While ICVCalc in Excel is aimed at an audience specialized in LCA, and permits a certain degree of customization of the calculation structure, ICVCalc web is intended for an audience that is familiar with agricultural systems, but not necessarily with the LCA technique.

¹⁹ The technosphere is the global system comprised of materials, artifacts, and flows created or managed by human activity which interact with the biosphere, lithosphere, hydrosphere, and atmosphere.

RenovaCalc – a tool for the agroenergy sector in support of the National Biofuels Policy

As mentioned above, RenovaBio is the National Biofuels Policy. Established by Law 13,576/2017, its main objective is to expand the share of biofuels in the Brazilian transport matrix which are produced more sustainably, thus contributing to decarbonization of the sector, in line with the commitments made by Brazil at the Paris Climate Conference (2015).

To implement RenovaBio, at the request of the Secretariat for Petroleum, Natural Gas and Biofuels within the Ministry of Mines and Energy (MME), a team composed of Embrapa Environment, the State University of Campinas, the Brazilian Biorenewables National Laboratory, and Agroicone developed RenovaCalc,²⁰ a tool for estimating the carbon intensity of biofuels (Matsuura et al., 2018). In the current public version, the calculator works with four types of biofuels: ethanol, biodiesel, biomethane, and aviation biokerosene, obtained through nine technological pathways (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, 2022).

RenovaCalc's methodological basis is the attributional LCA, focused exclusively on the "climate change" impact category and spanning "from well to wheel", in other words, accounting GHG emissions throughout the entire production chain, from extraction of natural resources, acquisition, production, and processing of biomass through its conversion into biofuel, to combustion in engines, and including all stages of transportation (Matsuura et al., 2022).

²⁰ Available at: <https://www.gov.br/anp/pt-br/assuntos/renovabio/renovacalc>

RenovaCalc has some advantages over other carbon accounting tools applied to international agroenergy policies: a) it allows the use of primary data, detailing the specific profile of the biofuel producer; b) it provides the entire calculation structure in an open manner, ensuring transparency; and c) it operates on Microsoft Excel software, which is widely used. In general terms, RenovaCalc requires two sets of data to be filled in by the user: agricultural data and industrial data. For the biomass production phase, the quantities of agricultural and energy inputs consumed must be reported, along with the area and volume of production. For the biofuel conversion phase, data on product and co-product yields must be entered, as well as energy consumption and other industrial inputs.

RenovaCalc estimates GHG emissions from the agricultural and industrial processes which, combined with background emissions (from the Ecoinvent database), result in the carbon intensity (CI) of the biofuel life cycle, expressed in g CO₂eq/MJ. The CI of the biofuel, subtracted from the CI of its equivalent fossil fuel (for example, gasoline, in the case of ethanol, or diesel, in the case of biodiesel), results in the Nota de Eficiência Energético-Ambiental (Energy-Environment Efficiency Score, NEEA), an indicator that represents the mitigation of GHG emissions due to the introduction of the biofuel into the transportation matrix as a substitute for the fossil fuel.

The NEEA is used to calculate decarbonization credits (CBios), environmental assets traded on the stock exchange. Each CBio corresponds to one ton of CO₂eq avoided. The “retirement” (in other words, permanent removal) of CBios mitigates the GHG emissions defined in RenovaBio’s annual targets. Between 2020 and February 2025, the program had already mitigated more than 160 million tons of CO₂eq.

Livestock carbon footprint calculator – efforts to increase efficiency and mitigate emissions from Brazilian cattle farming

Embrapa’s efforts to help increase production efficiency and mitigate GHG emissions resulted in the development of the Calculadora de Pecuária de Baixo Carbono (Low-Carbon Livestock Calculator, CPBC). The CPBC is a tool for calculating the carbon footprint of a kilogram of meat or milk produced, expressed in kg of CO₂eq/kg of product. The tool calculates enteric methane emissions from animal digestion and the methane produced by manure management from small, medium, and large rural operations. This calculator takes into account the carbon footprint of the food used or produced on the farm and destined for animal feed, and is aligned with Embrapa’s platform for generating agricultural inventories in life cycle assessment studies (ICVCalc). The CPBC also estimates carbon emissions and removals resulting from land use change, as well as potential removals on properties that adopt integrated crop-livestock-forestry (ICLF) or integrated livestock-forestry (ILF) systems, which include trees where most of the carbon is stored. The mathematical models are based on the Intergovernmental Panel on Climate Change (IPCC) (Ogle et al., 2019), the FAO Livestock Environmental Assessment and Performance Partnership (LEAP) guidelines (Food and Agriculture Organization of the United Nations, 2015) and the ISO 14040, 14044 (International Organization for Standardization 2006a, 2006b) and 14067 (International Organization for Standardization, 2018) standards.

Low-carbon beef and milk production starts from the premise that reducing emissions is a challenge, since it depends on the level of technology that each farm adopts and the maturity of the production system.

In Brazil, the wide diversity of climate and soil conditions allows for different technological combinations, resulting in strong contrasts between production systems. As a result, there is no single adjustment pathway for all systems and environments. Considering the different possible GHG mitigation and removal strategies, various technologies can be adopted, promoting direct or indirect emission reductions. Even within this context of complex systems and possible trajectories, the CPBC allows producers and processors to manage the technical and environmental performance of products.

Once the input information has been filled in, the tool generates the results for net emissions per kilogram of product for the user, and also indicates the main emissions sources. The entire process of calculating and generating results is incorporated into a platform that manages the indicators for each property. The platform can also be used to manage the performance of suppliers over time, or to simulate technologies that can improve the performance of each production system. For industry, it is a digital system that securely and quickly aggregates data from its suppliers, technicians, and production systems. It can be used to develop commercial arrangements, through collaborations between companies in a production chain interested in promoting the introduction of sustainable practices on livestock farms, with a focus on low-carbon livestock farming as a market differential, for example. New business models can be developed, including training activities and performance monitoring for rural properties throughout Brazil. Another opportunity is for producers and primary processing industries (dairies and slaughterhouse) to join Embrapa's low-carbon protocols, with support from calculators and certification schemes.

Since 2012, Embrapa has been conducting studies on cattle production protocols with a focus on efficiency and mitigating GHG

emissions. Initial efforts focused on production systems or on-farm activities based on good agricultural practices and technological processes listed in the federal government's Plano Setorial de Mitigação e de Adaptação às Mudanças Climáticas para a Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura (Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low-Carbon Economy in Agriculture, also known as the ABC Plan), Plano Nacional de Agricultura de Baixa Emissão de Carbono (National Low-Carbon Agriculture Plan, for the 2010–2020 period) (Brasil, 2012), and the Plano de Adaptação e Baixa Emissão de Carbono na Agricultura (Adaptation and Low-Carbon Agriculture Plan, ABC+ Plan, for the 2021–2030 period) (Brasil, 2021).

Along these lines, protocols for products such as low-carbon beef (Almeida; Alves, 2020), low-carbon leather (Jacintho et al., 2024), low-carbon calf, and low-carbon milk (currently under development) have been proposed; these efforts involve traceability and third party certification (with MRV-type verification), as well as mandatory requirements such as a ban on the use of fire and deforestation, based on the Pacto Setorial da Pecuária (Livestock Sector Pact) (Sustainable Amazon Forum, 2008).

The CPBC is developing integrated activities to structure a tropicalized database on emissions from agricultural inputs, as well as spreadsheets to collect data from the meat and leather industry, in order to express the carbon footprint per livestock product in accordance with global demands for more efficient and sustainable farming.

Reducing the carbon footprint of yellow melons

Studies on the carbon footprint of yellow melons were carried out between 2011 and 2014 in the two main producing regions of Brazil: Baixo

Jaguaribe-Apodi, on the border between Ceará and Rio Grande do Norte, which accounted for 97% of production destined for export in 2024 (Brasil, 2024), and the Sub-mid São Francisco River Basin, on the border between Pernambuco and Bahia, with production that mainly goes to the domestic market. The carbon footprint of melons produced in Ceará and Rio Grande do Norte was assessed per kilo of fruit exported, based on global warming potential (GWP) as defined by the IPCC (2006), considering a 100-year horizon. The study compared: a) the commercial monocropping system adopted by farms in the region (Figueirêdo et al., 2013) and b) the rotation system with grasses and legumes, in an experimental area (Barros et al., 2019). In the Sub-mid São Francisco region, the footprint was estimated for both commercial monocropping and rotation with plant cocktails in experimental areas, with the results expressed per kilogram of melon transported to the Companhia de Entrepósitos e Armazéns Gerais de São Paulo (CEAGESP, the city of São Paulo's main wholesale produce hub). In this case, the IPCC's GWP (2013) was adopted, which revised the methane value from 25 to 36 (Santos et al., 2018). These studies considered all stages of the chain: LUC production and transportation of inputs, seed and seedling production, and melon

cultivation, as well as post-harvest, packaging, and transportation to different destinations.

The results of these studies in two different locations (Figure 6.5) showed that the average carbon footprint of melons from the monocropping system, considering production for less than 20 years in areas occupied with Caatinga vegetation, was higher than that of the rotation system with green manures (experimental areas): between 0.71 and 0.75 kg CO₂eq/kg of melon for monocropping, and between 0.52 and 0.58 kg CO₂eq/kg of melon for the rotation system. The authors observed that the footprints in the rotation systems could be reduced even further if nitrogen from green manures replaced the use of synthetic nitrogen fertilizers, even if only partially (Barros et al., 2019; Santos et al., 2018). Additionally, shipping melons to the port of New York instead of Rotterdam reduced the footprint of exported melons by 2% (Barros et al., 2017).

Analysis of the processes related to the carbon footprint of monocropping melons indicated that production of the inputs used in the field and melon production itself were the processes that contributed most to this footprint in the Jaguaribe-Apodi region (Figure 6.6). GHG emissions from the production of nitrogen

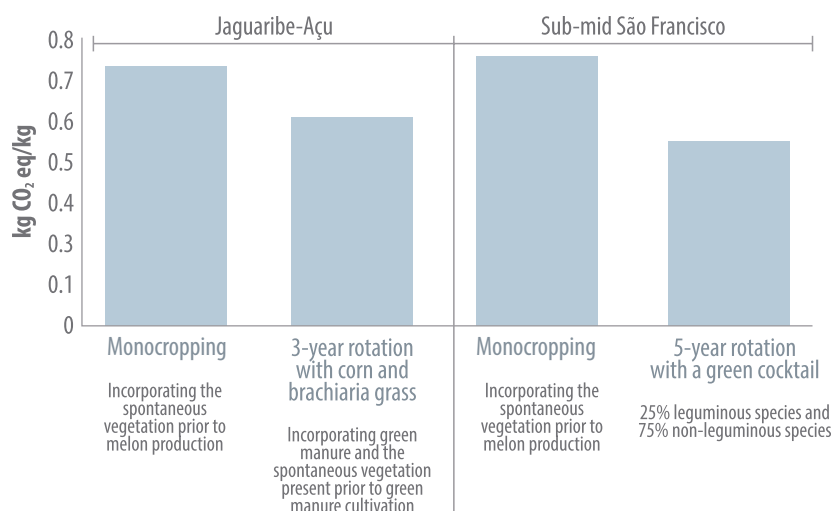


Figure 6.5. Carbon footprint of melons in a monocropping system and in rotation with green manures.

Source: Adapted from Figueirêdo et al. (2013), Barros et al. (2017), and Santos et al. (2018).

fertilizers and plastics (ground covers and plastic trays) played the most significant role in the accounting for emissions from the production of inputs. Emissions from LUC, when the area with Caatinga vegetation was converted into agricultural land, were the main cause of the total emissions generated in the field (Figueirêdo et al., 2013).

As an innovative solution to reduce this footprint, adjustment scenarios were proposed for commercial monocropping in the Jaguaribe-Apodi region: a) using fertilizers as recommended in the scientific literature; b) reducing the use of plastics, considering that some farms did not use trays; and c) planting in areas that had already occupied by agricultural production for over 20 years, which was the case observed on some farms (Figure 6.6). The footprint evaluation in these scenarios showed that the farms in the Jaguaribe-Apodi region used 33% more nitrogen than recommended for the crop, which could be reduced, leading to a 6% smaller footprint (Scenario 1). Establishing production in an area that had already been deforested over 20 years before would decrease the footprint of monocropping by 24% (Scenario 2), while eliminating the use of plastic trays to prevent the melon from coming into contact with the ground cover in the field would reduce the footprint by 13% (Scenario 3). Combining these scenarios would result in a 44% reduction in the

footprint of monocropping melons (Figueirêdo et al., 2013).

According to Santos et al. (2018), the main processes that contributed to the carbon footprint of melons in rotation with a plant cocktail in the Sub-mid São Francisco region were:

- Transporting the melons by road to São Paulo (accounting for 58% of the footprint);
- Establishing the crop in an area that had been deforested for less than 20 years (20%);
- Using cardboard packaging to transport the melons (20%); and
- Producing and applying synthetic nitrogen fertilizers in the field (18%).

The innovation solution in this case consisted of replacing transport exclusively by road with a combination of road and ocean transport to São Paulo, establishing the crop in an area that had been free of deforestation for more than 20 years, and using only green manure for nitrogen fertilization (since the amount of nitrogen offered by the manure was more than the crop needed), reducing impacts by 30%.

Reducing the water footprint of yellow melons

In order to reduce the water footprint of the melons grown in the Northeast, the key is to

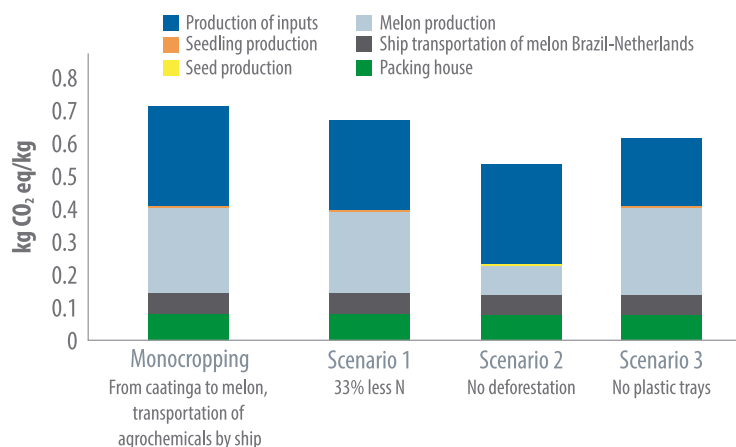


Figure 6.6. Analysis of scenarios that contribute to reducing the carbon footprint of monoculture melons in the Jaguaribe-Apodi region.

Source: Adapted from Figueirêdo et al. (2013).

increase the efficiency of water use in irrigation and to produce at times when water is less scarce. This is one of the conclusions of the LCA study and water scarcity footprint calculations for yellow melon production in the country's two main producing regions, both in the Northeast.

A crop's water scarcity footprint considers the various processes associated with its life cycle and is calculated by multiplying two factors: the crop's water consumption per kilogram of product, and the region's scarcity index, which indicates its vulnerability to reduced water availability (Figueirêdo et al., 2014; Santos et al. 2018). In the melon study, this calculation considered the average water consumption per process (for example, fertilizer production and agricultural production) and the scarcity indices for the main regions where the processes take place, weighting the consumption and the index according to the proportion of each region.

As for water consumption to irrigate the melons, the volume of water and the quantity of production per cycle as reported by the farmers were compared with the crop's gross water requirement, calculated from the reference evapotranspiration during the growing months (in a 70-day cycle), the actual rainfall in the producing region, the crop coefficient (FAO, 1997), and the efficiency of the irrigation system (in this case, drip irrigation).

To calculate the scarcity index, the Water Stress Index (WSI) was used, in the melon study produced in the Jaguaribe-Açu region, which normalizes the value of a crop's footprint in relation to a global reference value (Figueirêdo et al., 2014). The scarcity index used in this evaluation is measured in L H₂Oeq/kg of product, and was calculated by Ridoutt and Pfister (2010). In contrast, the Sub-mid São Francisco study only assessed water consumption during the melon life cycle (Santos et al., 2018), without calculating the water scarcity footprint.

The volume of water consumed to irrigate the melons was found to be greater than the crop's water requirement, in both the Jaguaribe-Apodi and the Sub-mid São Francisco regions. On the Jaguaribe-Apodi farms, the average volume of reported irrigation water varied from 186 to 202 L/kg of melon depending on the production period, which runs from July to February, with the lowest water consumption from July to September. A comparison between the volume applied and the quantity required for the crop showed that 39% more water than necessary was applied to melon crops from September to November, while 160% more water was applied between December and February (the period with the lowest irrigation requirements) (Figueirêdo et al., 2014). Also in the Sub-mid São Francisco region, comparison between the volume of water applied during the growing season (July to December) — 9,000 m³/ha in any month — and requirement of this crop (2,700 m³/ha, on average) demonstrated excessive use of this scarce resource in the Semi-Arid region of Brazil's Northeast (Santos et al., 2018).

Excessive water use resulted in lower productivity in the Jaguaribe-Apodi region (Figueirêdo et al., 2014). The highest yield (40 t/ha) was achieved when the lowest irrigation volume was used (89 L/kg), while the lowest yield (14 t/ha) occurred when the highest irrigation volume was applied (446 L/kg).

The average water scarcity footprint was 135.40 L H₂Oeq/kg for melons produced in the Jaguaribe-Apodi region and exported (Figueirêdo et al., 2014). Total water consumption during the life cycle of melons in this region was 197.90 L/kg, with 98.6% of this total coming from irrigation. The highest average scarcity rate was associated with fertilizer production, considering that in 2010 the main producing regions were: Chile (63% of production), Portugal (15%), Israel (10%), and other countries (12%). However, water consumption during fertilizer production

accounted for only 0.5% of total water consumption in the melon's life cycle. Therefore, the key to reducing this footprint is to boost the efficiency of water use in irrigation, and intensify production in less scarce months.

Reducing carbon and water footprints in mango production

LCA and carbon/water footprint calculation also help solve problems related to carbon emissions and water scarcity in mango production. The mango footprint assessments took place in the Sub-mid São Francisco region, which was responsible for 92% of Brazil's mango exports in 2024 (Brasil, 2024). The analyses were carried out per kilogram of mango, taking into account the production and transportation of inputs, LUC, and production of seedlings and mangoes in experimental areas (Dias et al., 2020), as well as post-harvest treatment and packaging in commercial monocropping areas (Müller Carneiro et al., 2019).

The carbon footprint of the commercial monocropping system was evaluated considering the IPCC's GEE GWP (2007) for 100 years. Meanwhile, the mango footprint in the experimental area (whether plant cocktails was used or not) was evaluated considering the IPCC's GWP (2013). Both studies considered that the mango orchards were established in areas previously occupied by Caatinga vegetation. The water scarcity footprint was assessed using the Aware (Available Water REmaining) method (Boulay et al., 2018), using country-level indices.

With regard to the carbon footprint (0.13 kg CO₂eq/kg of mango), the main factor in the commercial system was found to be the GHG emissions resulting from production and application of nitrogen fertilizers in the orchards (Müller Carneiro et al., 2019). Although the mango biomass sequestered more carbon than the Caatinga vegetation, this stock did not compensate for the carbon losses in the soil in

the monocropping system, or the GHG emissions from field production and the rest of the chain. But in mango production with green manure (experimental area), a negative carbon footprint was observed (-0.82 kg CO₂eq/kg of mango), 16% lower than the footprint observed in the monocropping plots (Dias et al., 2020).

The lower carbon footprint in the system using green manure resulted from the greater sequestration of carbon in the biomass and soil (6,964 kg CO₂eq/kg over eight years) provided by the plant cocktails (75% legumes and 25% non-legumes), which were kept in the ground as mulch and incorporated annually into the soil between the mango tree rows. In the plots without green manure, the carbon stock was 4,590 kg CO₂eq/kg over eight years.

Furthermore, in the scenario where the orchard was established in an area previously occupied by melons, the mango's carbon footprint was reduced by 78% compared to the situation where Caatinga vegetation was removed (Dias et al., 2020).

With regard to the water scarcity footprint (0.9 m³-eq/kg of packaged mango), in the commercial system, 78% of this impact was due to water consumption in irrigation (Müller Carneiro et al., 2019) and the remainder from sanitizing the fruit during the post-harvest and packaging stages. The average reported water consumption was consistent with the crop's gross water requirement, although the values for the establishment, growth, and full production stages differed.

The mango scarcity footprint in the experimental area with green manure, 2.82 m³-eq/kg of mango (Dias et al., 2020), was higher than the value of 0.9 m³-eq/kg of packaged mango observed in the commercial monocropping system, which also considered post-harvest (Müller Carneiro et al., 2019). This was mainly due to the lower mango production per hectare in the experimental area (6,379 kg/ha, with fewer mango trees to cover

the area with green manure) compared to the commercial areas, where the average was 34,700 kg/ha.

Reducing the carbon and water footprint of green coconuts

Calculation of the carbon and water footprints guides reduction of these impacts by recommending that coconut orchards be established in areas already occupied by agriculture and more efficient use of irrigation water and nitrogen fertilizers.

The study by Sampaio et al. (2021) on the carbon footprint and water scarcity of one kilogram of green coconut covered commercial production on six monocropping farms located in the states of Ceará, Alagoas, Sergipe, and Bahia. These states accounted for 59% of national production in 2023 (Associação Brasileira dos Produtores e Exportadores de Frutas e Derivados, 2025) and 57% of the value of coconut exports in 2024 (Brasil, 2024). This study considered the processes of LUC, production and transportation of inputs, and coconut production; one of the farms in Ceará utilized an organic system, while the others used a traditional system with various agrochemicals. The carbon footprint was calculated using the IPCC's GWP (2007), and the water scarcity footprint was estimated using the Aware method (Boulay et al. 2018).

The carbon footprint for coconut ranged from 0.12 (on the farm in Alagoas) to 0.36 kg CO₂eq/kg of coconut (on one of the four farms in Ceará using a traditional system) in cases where the orchard replaced native Caatinga vegetation. These farms showed significant differences in productivity (60 t/ha in Alagoas and 19 t/ha in Ceará), GHG emissions from LUC (higher in the Caatinga vegetation regions in Ceará and Bahia), and the amounts of fertilizer applied (higher on the Ceará farm).

On all farms, GHG emissions mainly resulted from LUC and the use of nitrogen fertilizers. If the orchards were located in areas previously occupied by annual crops, there would be a 37 to 61% reduction in the carbon footprint, depending on the region of the farm. As for the use of fertilizers, discrepancies were observed between the amounts of nitrogen, phosphorus, and potassium applied on all farms and the values indicated by Fontes and Ferreira (2006). For example, using fertilizers according to these recommendations on the farms in Ceará would reduce the footprint by at least 51%, depending on the farm.

Meanwhile, the water scarcity footprint of green coconuts varied from 0.3 to 0.7 m³eq/kg on the farms in Ceará. Again, water consumption for irrigating the coconut trees was the biggest culprit, accounting for between 68 and 92% of the footprint, according to the farm. On five farms, the volume of water applied per plant was more than necessary (between 12 and 131% higher, depending on the farm), while on two farms it was lower, with direct impacts on decreased fruit size and coconut water production.

Furthermore, in each state, the location of the farms in different river basins with significant coconut production was found to influence the coconut water scarcity footprint values, due to the differences in the scarcity indices. Considering the annual scarcity index of the river basins (Boulay et al., 2018), the results were as follows: in Sergipe, the smallest footprint occurred in the Sergipe state basin (0.28 m³eq/kg) and the largest in Vaza Barris (0.62 m³eq/kg); in Ceará, the highest value was recorded in the metropolitan basin (0.76 m³eq/kg) and the lowest in Curu (0.33 m³eq/kg); in Bahia, the largest footprint occurred in the Recôncavo Sul basin (0.67 m³eq/kg) and the lowest in Itapicuru (0.19 m³eq/kg); and in Alagoas, the São Miguel, Coruripe, and Piauí basins had the largest footprint (0.42 m³eq/kg), while Camaragibe had the lowest (0.22 m³eq/kg).

Life cycle assessment of wheat – Global Warming Potential

The production chain for wheat and derived products is part of other food production chains that cause GHG emissions, while it is simultaneously impacted by global climate change. Studies on the environmental impacts of wheat grown in subtropical and tropical environments are still scarce, creating a knowledge gap that needs to be filled. Among the various initiatives to promote the growth of Brazilian wheat production, the country has contributed to advancing scientific knowledge and promoting the sustainability of the wheat production chain (Figure 6.7). Efforts are focused on identifying the environmental impacts of the Brazilian wheat cultivation and flour production system, as well as proposing strategies for mitigating and adapting to climate change.

Within this context, the first in a sequence of studies on the LCA of wheat and wheat flour was carried out in the homogeneous regions where wheat cultivars are adapted in Brazil. The initial focus was on the GWP or carbon footprint

impact category, but others are also being examined, such as ecotoxicity, eutrophication, human toxicity, terrestrial acidification, and water consumption. Based on primary data from 61 farms, a grain processing plant, and a mill located in one of Brazil's main wheat-producing regions, Giongo et al. (2025) reported the environmental impacts of wheat and wheat flour considering four processes: wheat cultivation, transportation, grain processing, and milling for flour production. The life cycle of wheat production (from the cradle to the farm gate) accounted for 67 to 98% of the potential impact on the categories assessed for flour production.

With regard to the GWP impact category, the wheat cultivation stage in Brazil emitted an average of 0.50 kg CO₂eq/kg of wheat on small and large farms (Giongo et al., 2025). This value is still high compared to wheat produced in Germany (Riedesel et al., 2022) and Australia (Simmons et al., 2019), but is below the world average (Feng et al., 2023) and competitive with European countries such as Italy (Verdi et al., 2022) (Figure 6.8).

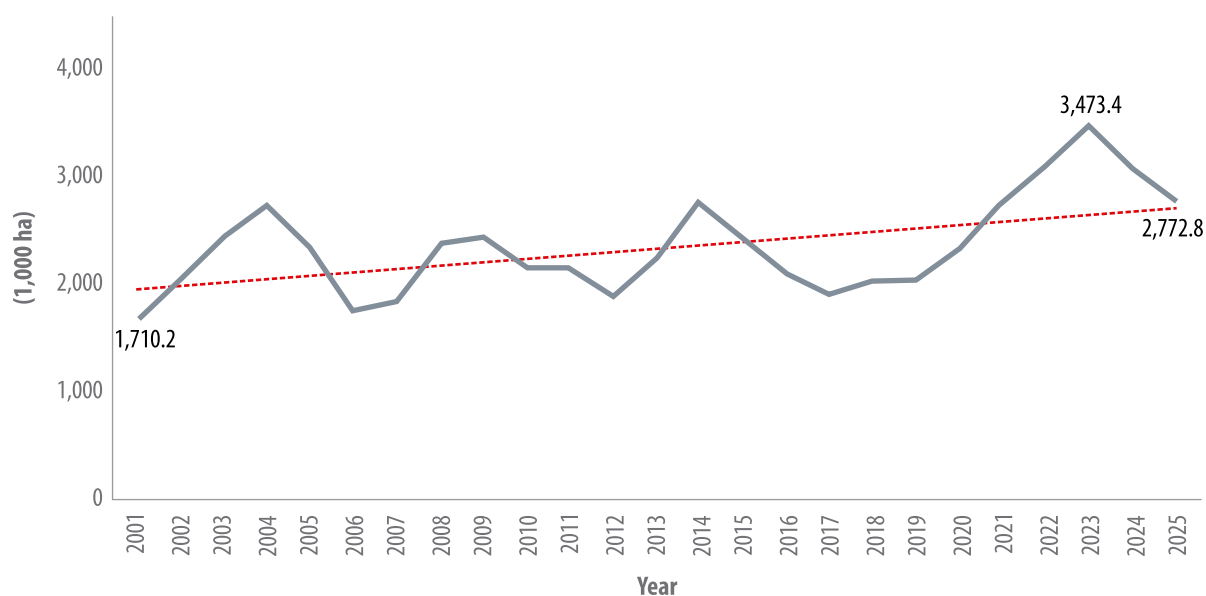


Figure 6.7. Wheat area in Brazil (in thousand ha).

Source: CONAB (2025b).

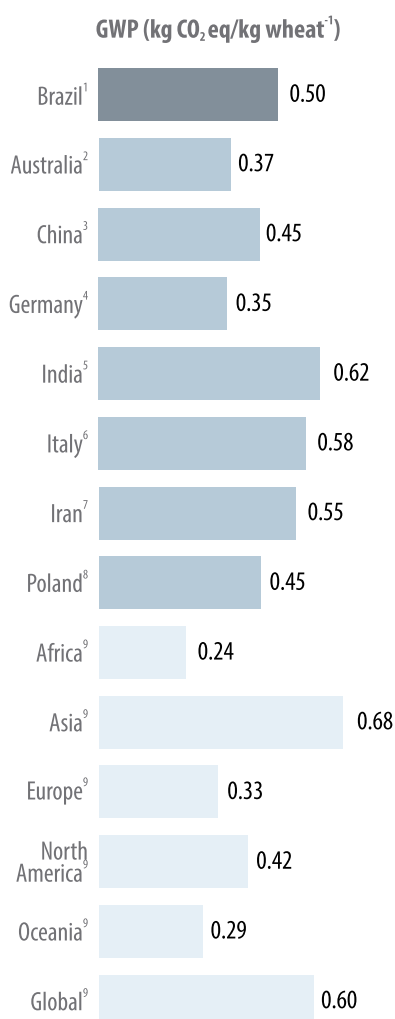


Figure 6.8. Comparison of the carbon footprint for production of 1 kg of wheat in different countries around the world.

Source: ¹Giongo et al. (2025); ²Simmons et al. (2019); ³Shao et al. (2024); ⁴Riedesel et al. (2022); ⁵Nayak et al. (2023); ⁶Verdi et al. (2022); ⁷Tahmasebi et al. (2018); ⁸Pishgar-Komleh et al. (2020); ⁹Feng et al. (2023).

Scenario analysis also indicated opportunities to reduce the carbon footprint in the wheat cultivation stage by up to approximately 36%, by replacing nitrogen fertilizer sources (scenario 1) and using more productive cultivars (scenario 2) (Giongo et al., 2025). In scenario 1, large and small farms that applied 155 and 148 kg/ha of urea, respectively, replaced this input with 265 and 253 kg/ha of CAN (calcium ammonium nitrate) produced in Europe; this

substitution generates lower impacts in terms of both fertilizer production and emissions in the field. Other technologies with the potential to mitigate nitrous oxide emissions and increase the efficiency of nitrogen absorption by plants include the use of slow-release nitrogen sources, green ammonia (Galusnyak et al., 2023), and wheat cultivars with biological nitrification inhibition (BNI) capacity (Wang et al., 2021; Lu et al., 2024).

Another strategy associated with both mitigating and adapting to climate change, which has potential to reduce wheat's carbon footprint at the cultivation stage, is the emerging challenge of genetic improvement to increase production efficiency in the face of the climate scenarios predicted for the global South and North. In a Brazilian study (Giongo et al., 2025) that used scenario 2 and was based on nine years of evaluating wheat genotypes (Castro et al., 2023), cultivars that produced an average of 4,039 kg/ha and 3,569 kg/ha on large and small farms, respectively, were replaced with a cultivar with an average yield of 5,876 kg/ha. Current productivity gains, however, may be insufficient to meet future demand for wheat, which requires concerted efforts to diversify, improve, and intensify genetic improvement (Cavalet-Giora et al. 2024), cultural practices and soil and water management, and conservation to increase productivity and ensure sustainability. For this reason, it is fundamental to understand the genetic mechanisms that promote adaptive success for profitable and stable wheat production in the future (Zhou et al., 2020), especially as the climate becomes more unstable (Xiong et al., 2024). Although adaptation of wheat varieties to future climatic conditions is crucial, a complete understanding of this process remains limited (Han et al., 2025), and advances need to be incorporated into predictive scenarios of environmental impacts, such as those used in LCA.

The carbon footprint of Brazilian flour varied between 0.67 and 0.80 kg CO₂eq/kg of flour made from wheat grown on large and small farms, respectively (Giongo et al. 2025). These values are lower than those reported for wheat flour produced in Spain (0.89 kg CO₂eq/kg flour; Câmara Salim et al., 2020) and Italy (0.95 kg CO₂eq/kg flour; Kulak et al., 2015). Nitrogen and phosphate fertilizers were the emission sources that had the greatest impact on the cultivation stage, where scenarios considered replacing urea with CAN (scenario 1) and using more efficient and productive cultivars (scenario 2). The transportation, grain processing, and wheat milling stages for flour production made the smallest contributions to the carbon footprint. However, replacing hydroelectric energy with photovoltaic energy in the grain processing (scenario 3) and wheat milling (scenario 4) stages was found to be an opportunity to reduce the footprint of wheat flour produced in Brazil. After applying the four scenarios, it was possible to reduce the carbon footprint of Brazilian wheat flour to 0.48 and 0.52 kg CO₂eq/kg of flour, using wheat from large and small farms respectively, showing average values that are very competitive compared to other regions of the world (Figure 6.9). These results are close to the lowest levels reported in France and Portugal, both with a value of 0.50 kg CO₂eq/kg of flour (Kulak et al., 2015).

The studies found that the carbon footprint varied between 0.48 and 1.66 kg CO₂eq/kg of flour (Kulak et al., 2015; Câmara Salim et al., 2020; Pourmehdi; Kheiralipour, 2020; Giongo et al., 2025). This variation is to be expected, considering the different soil and climatic conditions and management practices, which vary on a regional scale (Câmara Salim et al., 2020) and represent opportunities for improvement.

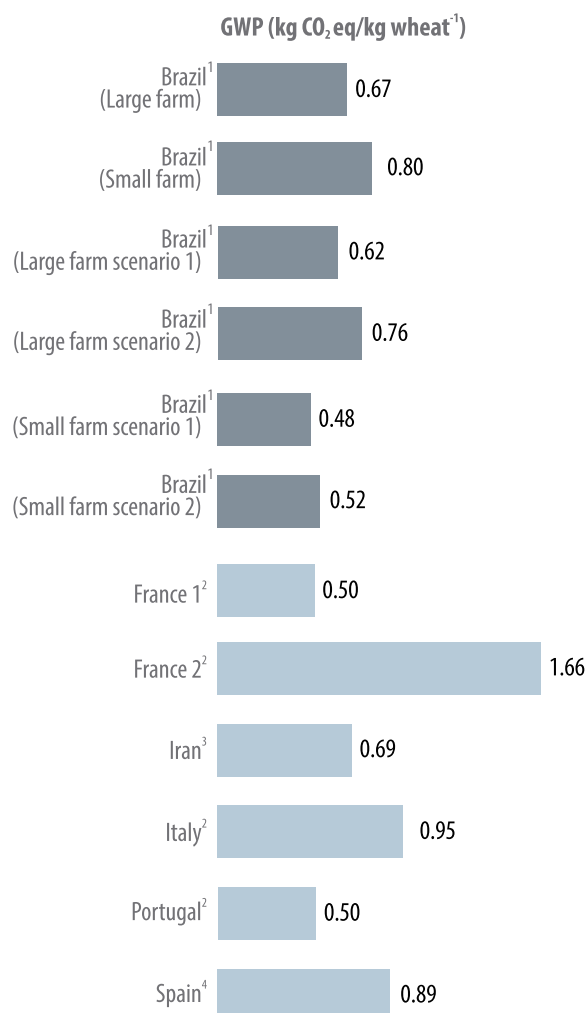


Figure 6.9. Comparison of the carbon footprint for production of 1 kg of wheat flour in Brazil and other countries.

Source: ¹Giongo et al. (2025); ²Kulak et al. (2015); ³Câmara Salim et al. (2020); ⁴Pourmehdi and Kheiralipour (2020).

Life cycle assessment of wheat – other environmental impact categories

GWP, expressed in CO₂ equivalent, is the most widely used category for assessing the environmental impact of agricultural systems on the climate, and also most commonly used for discussing climate change mitigation and adaptation policies. However, it is important to

note that other categories of environmental impact are equally relevant for multifactorial analysis of the sustainability of agricultural food production chains. In the case of Brazilian wheat, the LCA study includes other impact categories, such as potential for water consumption, terrestrial acidification, eutrophication²¹ in freshwater, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and human toxicity (cancer and non-cancer), using the Aware and ReCiPe methods (Giongo et al., 2025). For example, Brazilian wheat flour production has notably positive performance in relation to freshwater eutrophication and marine eutrophication. These two impact categories are directly related to the amount of fertilizers used and their potential for leaching into agricultural areas. The potential²² for marine eutrophication resulting from the leaching of nitrogen compounds in wheat flour production in Brazil is 500 to 1,500 times lower than for production in countries such as France, Italy, and Portugal (Kulak et al., 2015; Giongo et al., 2025). Replacing urea with CAN may further reduce the potential impact in this category (Figure 6.10).

Another example of the good environmental performance of Brazilian rainfed wheat flour can be seen in the low values for freshwater ecotoxicity and human toxicity potential compared to values observed in countries such as France and Italy. Finally, this same comparative analysis identified opportunities for improvement in relation to the potential for terrestrial acidification and terrestrial ecotoxicity, where values were higher than those recorded

in European countries (Kulak et al., 2015; Giongo et al., 2025).

Integrated and systemic analysis of GWP with other impact categories is essential for developing sustainable wheat production models that are suitable for each of the homogeneous regions where wheat cultivars are adapted in Brazil. This approach strengthens the design of programs such as the Low-Carbon Wheat Program, which strives to promote the sustainability of wheat production through good agricultural practices and technologies that reduce the net intensity of GHG emissions, increase productive, economic, and environmental efficiency, and boost the adaptive resilience of cultivation systems.

Future prospects

The climate emergency and the need to advance sustainable development, reflected in the commitments made in the Paris Agreement, require significant changes in agri-food systems. New technological standards must be based on clean production systems, with a positive carbon balance, efficient use of water and fertilizers in production, and investments in the conservation and sustainable use of biodiversity. Agricultural growth should be based on a balance between production and environmental performance. Increased efficiency could guarantee greater agricultural production, without the need to clear new areas.

The road to sustainable agriculture is paved by Brazil's public policy framework, which includes the ABC Plan, RenovaBio, Programa Nacional de Solos do Brasil (National Soil Program for Brazil, PronaSolos), National Bioinput Program, ZARC, Política Nacional de Pagamento por Serviços Ambientais (National Policy for Payment for Environmental Services), ratification of the Acordo de Negociação sobre Biodiversidade

²¹ Eutrophication is a process of excessive enrichment of nutrients, especially nitrogen and phosphorus, in bodies of water (such as lakes, rivers and reservoirs), which leads to accelerated growth of algae and aquatic plants.

²² The term "potential" is conventionally used, because LCA does not deal with actual impacts, but rather the potential for a given product or service to generate impacts.

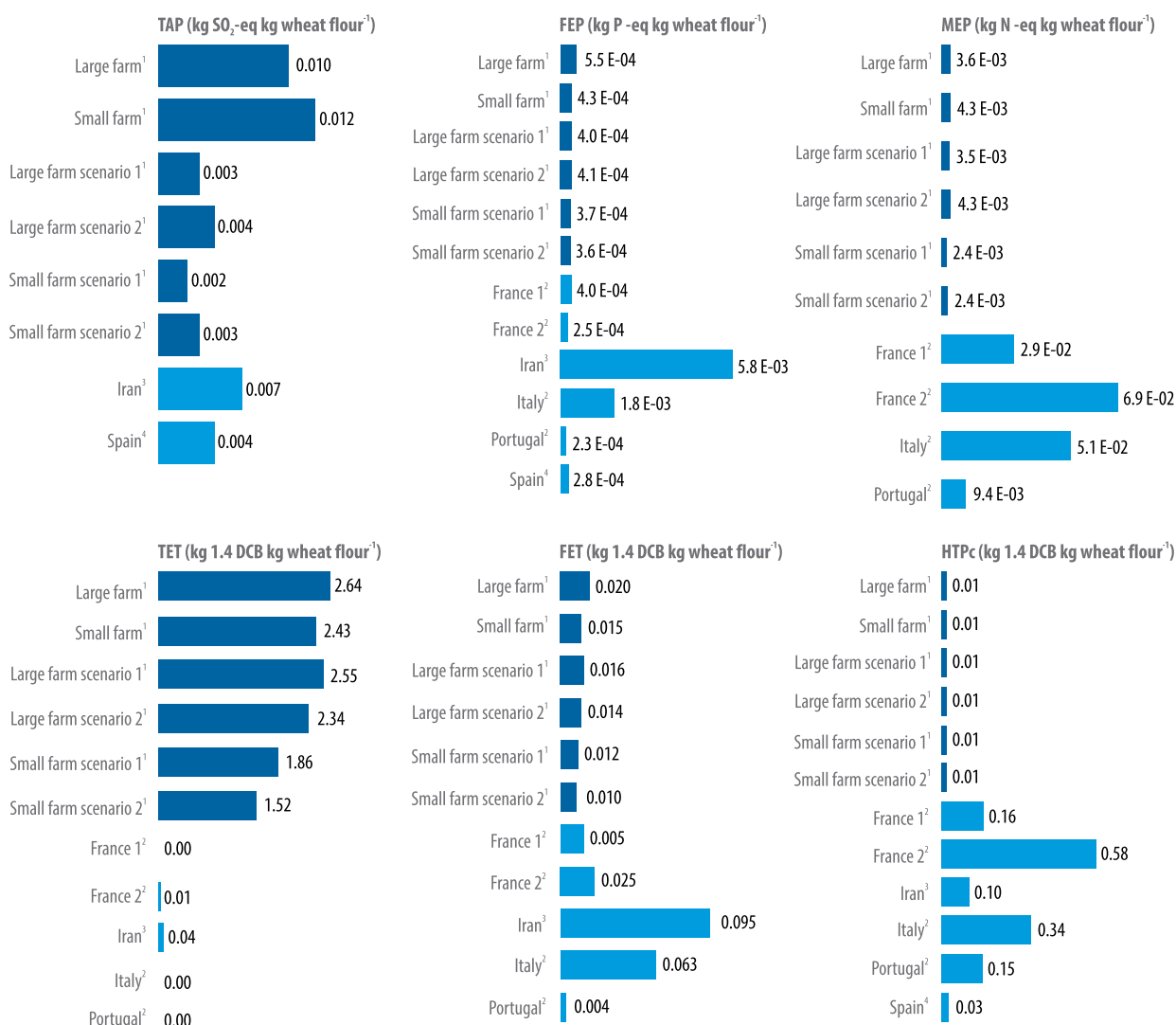


Figure 6.10. Comparison of environmental impact categories for the production of 1 kg of wheat flour in Brazil and other countries, in the current context and in proposed scenarios. TAP = terrestrial acidification potential; FEP = freshwater eutrophication potential; MEP = maritime eutrophication potential; TET = terrestrial ecotoxicity; FET = freshwater ecotoxicity and HTPc = human toxicity potential cancer.

Source: ¹Giongo et al. (2025); ²Kulak et al. (2015); ³Câmara Salim et al. (2020) and ⁴Pourmehdi and Kheiralipour (2020).

(Negotiating Agreement on Biodiversity), the Native Vegetation Protection Law (also known as the Forest Code), Política Nacional de Recursos Hídricos (National Water Resources Policy), and the national programs to prevent and control deforestation in the different biomes.

In this context, it is essential to develop and improve impact assessment metrics that highlight the competitive advantages of tropical

agriculture and indicate points for improvement, contributing to decarbonization, efficient use of water resources, and minimization of environmental impacts.

Because of its complete and robust nature and its transparency and scientific credibility, the LCA has become the foundation of many certifications, to address non-tariff barriers in international trade and for investments.

The main challenges for advancing the application of LCA in tropical agriculture include:

- **Improving** models and tools for land use change, including improving data sources on land use dynamics and carbon stocks in soil and biomass.
- **Improving** dispersion models and emission factors for substances originating in agricultural processes and destined for environmental compartments, in tropical soil and climate conditions, considering the complexity of production systems.
- **Generating** and **inserting** updated life cycle inventory data into international forums and databases for the main chains of agricultural products and inputs, ensuring greater reliability and credibility in impact assessments. This is essential to guarantee the competitiveness of Brazilian agriculture and to correct misunderstandings about this sector, guiding public policies and initiatives by both the government and the productive sector.
- **Providing** LCA support tools for agricultural products, boosting the efficiency and consistency of metrics, and supporting assertive actions for decarbonization and efficient use of irrigation.
- **Generating** the carbon footprint, water footprint, and environmental profile of Brazil's leading export products and indicating recommendations and management practices to improve these profiles.
- **Integrating** LCA tools with other sustainability criteria and indicators, including value for native vegetation reserves associated with Brazilian rural landscapes.
- **Disseminating** the LCA culture in agri-food chains, making it possible to integrate and harmonize data and communicate impacts and externalities.

Embrapa, which has been developing LCA studies for agricultural systems since 2009, stands out as a reference on the subject in Brazil. LCA inventories, tools, and studies like those presented in this chapter have generated intense demand for applications in a wide variety of contexts.

This chapter has provided a brief overview of the solutions that can be applied to measure and guide activities to attain a more favorable carbon balance in agriculture, along with various other environmental co-benefits.

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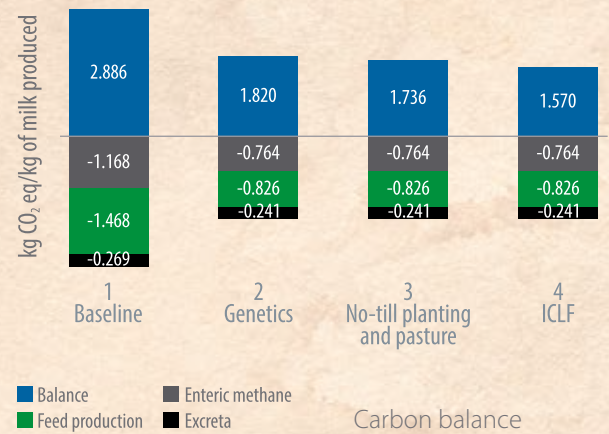
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Sample result from Embrapa's low-carbon milk calculator

The carbon balance is calculated as the sum of emissions minus carbon removals in meat and milk production systems. To obtain the sum of emissions, Embrapa's low-carbon livestock calculator estimates the GHG emissions resulting from enteric fermentation, manure, and food production. To subtract removals, the calculator estimates carbon sequestration in agricultural soils, pastures, and tree trunks in integrated crop-livestock-forestry systems.

The figure below shows simulations in which the carbon balance of milk is represented in blue, and decreases as different complementary technologies are adopted.

- In the **first bar** on the left represents a conventional or "baseline" milk production result, characterized by grazing with low technology adoption.
- In the **second bar**, the farm started using superior genetics specialized in milk production, resulting in a 37% smaller carbon footprint.
- In the **third bar**, soil management was improved by adopting no-till farming in crops destined for animal feed and pasture intensification, resulting in a footprint 40% smaller than the baseline.
- In the **fourth bar**, trees were incorporated into the milk production system; they not only contribute to the comfort and well-being of the cows, but also sequester carbon in their trunks, resulting in a 46% smaller footprint than the conventional system.



Carbon balance of milk in systems with different technological profiles.



CHAPTER 7

Monitoring and inventories under the Paris Agreement, considering medium- and long-term challenges

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Introduction

Building a robust system for monitoring and inventorying greenhouse gas (GHG) emissions in the medium and long term is a strategic challenge for Brazil, especially considering the specific characteristics of tropical agricultural production systems and the obligations assumed as part of the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992) and the Paris Agreement. Since signing the UNFCCC in 1992 during Rio-92, Brazil has become a leading player in the global climate agenda, and was the first country to ratify the convention and establish a designated national authority, initially linked to Ministério da Ciência, Tecnologia e Inovação (the Ministry of Science, Technology and Innovation, MCTI). This pioneering spirit reflects the strategic importance the country attaches to the transparency and quality of the data reported in its national inventories, which serve as both internal management instruments and as tools for positioning itself on the international stage. The goal of developing a plan and infrastructure for medium- and long-term monitoring and inventory emerged in this context, in order to align Brazilian scientific and institutional capacities with the demands of the Enhanced Transparency Framework mechanism¹ (ETF) of the Paris Agreement (United Nations,

¹ The Enhanced Transparency Framework (ETF) is an improvement to the transparency mechanism under the Paris Agreement, and is intended to ensure comparability, completeness and consistency for GHG emissions estimates from all signatory countries.

2016), which came into force in 2024 with Biennial Transparency Reports² (BTRs).

The agricultural sector, which in this context is part of the broader scope of agriculture, forestry, and other land uses (“AFOLU”) in the 2006 guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2025) and obviously includes livestock, is a central pillar of the Brazilian economy and at the same time one of the country’s main sources of GHG emissions. Emissions of methane (CH₄) from livestock farming and irrigated rice production, and nitrous oxide (N₂O) from managed soils, along with land use changes associated with deforestation and agricultural expansion, highlight the complexity of characterizing these tropical systems. The 2006 IPCC guidelines, which were updated in 2019, provide the methodological framework for inventories based on the principles of Transparency, Accuracy, Completeness, Comparability, and Consistency (TACCC). However, applying these methods in a country as large as Brazil, which encompasses various biomes and countless agricultural practices, requires continuous efforts to improve that extend beyond the generic Tier 1 approaches³ and transition to Tier 2 and 3 levels, as shown in Table 7.1, with data and models adapted to the national reality.

The history of Brazil’s involvement in the UNFCCC shows a long-standing commitment to generating reliable national inventories. From the first National Communication (NatCom) in 2004,

through the Biennial Update Reports (BURs) and on to its First BTR in 2024, Brazil has made progress in the quality of its reports, relying on the expertise of the Brazilian Agricultural Research Corporation (Embrapa) from the beginning of this process. Embrapa has played a crucial role in supporting MCTI, providing activity data and specific emission factors for the agricultural sector, as well as contributing to estimates of emissions and removals from sub-sectors such as planted forests and waste. This work was institutionally formalized in 2024 through a Technical Cooperation Agreement between MCTI and Embrapa, which is intended to continuously improve the inventory and consolidate Embrapa as the technical and scientific coordinator of the agricultural subsector in the national inventory. This agreement reflects the need for a long-term partnership to address the challenges of monitoring and inventory, especially at a time of transition for the ETF, which requires greater rigor and frequency in the data presentation.

Characterizing tropical agricultural production systems involves multiple challenges that stem from both the limitations of the IPCC methodologies and the inherent complexity of the Brazilian context. Tier 1, which is widely used in initial inventories, is based on standard emission factors and global data, resulting in estimates that are conservative and not representative of local conditions. For example, methane emissions from livestock or carbon removals in integrated systems such as integrated crop-livestock-forestry (ICLF) and crop-livestock (CLI) systems are not adequately captured without refined domestic data. The shift to Tier 2, using national emission factors, and Tier 3, with specific models, is essential to go beyond the subtropics and reflect the reality of Brazilian tropical production systems, but requires investments in research, data collection infrastructure, and technical training. The low spatial resolution and intermittent nature of data collection initiatives have also hampered

² Biannual Transparency Reports are ETF instruments that aim to establish a base for comparing GHG emission and removal estimates between countries. Compared to the national inventories originally established under the convention, the BTR establishes a new common tabular format (CTF), a tool that ensures comparability between the data submitted by the various signatory countries of the Paris Agreement.

³ The convention uses the term “tier” to represent the level of approximation or detail adopted by the party to estimate the GHG emissions of each activity included in its inventory and reported in its BTRs. Table 7.1 presents the characteristics of the three tiers.

Table 7.1. Sensitivities and characteristics of the national GHG emissions inventory, considering the TACCC⁽¹⁾ principles and their unique details by tier.

Principle (TACCC)	Consistency of data series over the years - principle of Consistency		
	Comparability of data between countries - principle of Comparability		
	Transparency of the data presented, ensured by an independent review process - principle of Transparency		
	Mandatory for all countries and categories - principle of Completeness	Mandatory for all categories classified as key due to two factors: 1) Level, absolute variable, emissions ratio, or 2) Trend, relative variable, tendency to increase future emissions - principle of Accuracy	Optional and developed based on national methods and models that need to demonstrate increase - objective of transparency, accuracy, completeness, and consistency, without harming comparability

	Tier 1	Tier 2	Tier 3
Accuracy level	Low	Sufficient	Superior
Cost	Low	Moderate	High
International financing for developing countries	Fully funded by the Global Environment Facility (GEF)	Fully funded with agreed GEF resources	Not funded
Accounting for removals	Removals are not accounted	Removals can be accounted with the limitations of the standard Tier 2 method	Removals can be accounted, taking into account the unique characteristics of national production systems
Domestic data	Little or no need. Generic default parameters	Need to produce some type of domestic data, including emission factor and/or activity data applied to the standard Tier 2 method	Need to establish a systematic data acquisition strategy to justify robustness and improvement of the TACCC for the national method proposed as Tier 3
Level of exposure for sensitive data	Low risk of exposure for sensitive data	High level of exposure for sensitive data, particularly by improving the accuracy of estimates. Involves major efforts for data disaggregation	Moderate/low level of exposure for sensitive data, since primary data is used to feed the national model, and the goal is generally to assess the robustness of the data acquisition strategy
International scrutiny	Superficial attention, low priority	High attention, detailed review of recommendations	High attention, but a greater challenge for international reviewers

⁽¹⁾ Transparency, Accuracy, Completeness, Comparability and Consistency.

structural progress, highlighting the need for medium- and long-term strategic plans to ensure continuity and robustness.

Table 7.1 offers a summary of the sensitivities and characteristics of the national GHG emissions

inventory, considering the TACCC principles and their unique details by tier.

The colors shown in Table 7.1 represent a hierarchy: green corresponds to the most favorable or least restrictive condition; yellow

represents an intermediate condition; and red corresponds to a more unfavorable or inaccessible condition. Each specific row in the table includes the following representations:

TACCC: Tier 1 is shown in green, since it is less restrictive; Tier 2 appears in yellow, since it corresponds to an intermediate level of restriction; and Tier 3 is shown in orange due to a higher degree of restriction.

Accuracy: the situation is reversed: the most desirable condition is Tier 3 (classified as superior), while the least favorable is Tier 1 (classified as low).

Cost: Tier 1 is represented in green (classified as low), while Tier 3 is unfavorably classified in orange (high cost).

Financing: follows the same logic as cost - Tier 1 (green) is easier, while Tier 3 (orange) faces greater difficulties.

Accounting for removals: Tier 1 is classified unfavorably (orange), since it does not account for removals. Tier 3, on the other hand, is green, since it permits more objective estimates.

Domestic data: Tier 1 is shown in green due to ease of application, while Tier 3 requires greater investment and more accurate data.

Sensitive data exposure level: both Tier 1 and Tier 3 are represented in green, since they protect sensitive data for different reasons. Tier 2, on the other hand, exposes more data and therefore appears in orange.

International scrutiny: Tier 3 is depicted in yellow, because of its complexity and because it is not verified in such detail. Tier 2 concentrates the greatest verification efforts on the part of international reviewers, and is therefore orange.

The medium- and long-term challenges for developing monitoring for the agricultural sector under the Paris Agreement are the subject of this document, and the strategies proposed in this context aim to support the structuring of

a national system that strengthens domestic institutions, with emphasis on Embrapa's role as technical coordinator of this subcomponent of the inventory. The objective of this work is to establish a collaboration network with relevant domestic and international research institutions, academia, universities, and civil society in support of the national system coordinated by MCTI.

This plan should include the continuous generation of primary high-resolution spatial data, development of advanced analytical tools, and transition to Tier 3 in key categories of the agricultural sector such as livestock, managed soils, and land use. Embrapa, in partnership with MCTI, MAPA, and the private sector, can lead this process, catalyzing research and innovation efforts to address the unique characteristics of the tropics. The following sections detail how this plan could be structured, the expected benefits, and the challenges to be faced, taking into account the history of transparency in the UNFCCC and lessons learned in recent decades.

Historical context and strategic relevance

Brazil's commitment to transparency in agricultural emissions dates back to the signing of the UNFCCC in 1992 and was consolidated in Article 4 (Nações Unidas, 1992), which establishes the obligation to develop and publish national GHG inventories using comparable methodologies. Since then, the IPCC has been primarily responsible for providing these methodologies, evolving from the 1996 guidelines to the 2006 version, which today forms the basis of the Paris Agreement's ETF. The IPCC's efforts to improve these methodologies are ongoing, and they were refined in 2019, but their use has not yet become compulsory. Brazil, as the first signatory to the convention and a pioneer in institutionalizing a national authority, demonstrated its intention to lead the

climate agenda among developing (non-Annex I) countries early on. This role was reinforced by three NatComs (2004, 2010 and 2016) and three BURs (2014, 2017 and 2019), which incorporated data from the agricultural sector with the support of Embrapa, initially using the 1996 IPCC guidelines and more recently the 2006 rules.

The transition to ETFs in 2024 marks a new cycle of requirements, with BTRs demanding more frequent and accurate reporting. For the agricultural sector, this means improving the quality of data on activity (such as number of cattle or amount of nitrogen fertilizers, for example) and emission factors (like enteric methane per animal, or N₂O per kilogram of N applied), overcoming the limitations of Tier 1, which does not capture efficiency gains or tropical specificities. The proposed monitoring plan seeks to respond to this demand, in line with the UNFCCC's objective to stabilize GHG concentrations at levels that protect the climate system, food production, and sustainable development, in accordance with Article 2 of the Convention. In this sense, long-term infrastructure must integrate science, technology, and public policies to position Brazil as a leader in agricultural sustainability.

Challenges of tropical agricultural production systems and the role of Embrapa

Tropical agricultural production systems have unique characteristics that challenge IPCC methodologies, such as high climate variability, soil diversity, and the intensity of interactions between agriculture and forest. In Brazil, these specificities are evident in practices such as irrigated rice cultivation in the South, extensive livestock farming in the Midwest, and integrated systems in the Cerrado and Amazon. While the

2006 guidelines are more comprehensive than the 1996 ones, they still rely on local data to achieve higher levels of accuracy (Tier 2 and 3), which requires a robust national system for collecting and analyzing information. Table 7.2 presents a comparative analysis of the evolution of these IPCC guidelines over time and provides information and structures to be considered in moving towards a higher tier, with better compliance with the TACCC principles. Embrapa has been essential in this process, developing technologies such as BioAS, Netflora, and PlanejArroz, which can contribute directly and even indirectly to boosting the accuracy, consistency, and completeness of inventories, although the scale and continuity of these initiatives need to be expanded.

The monitoring plan must address challenges such as the lack of disaggregated primary data, dependence on global emission factors, and the absence of models adapted to tropical conditions. For example, methane emissions from livestock vary significantly between breeds and management systems, while carbon stocks in tropical soils depend on practices such as ICLF, which are not well represented in Tier 1. Embrapa, through its Technical Cooperation Agreement (ACT) with MCTI, is positioned to lead the generation of this data, cooperating with official platforms such as the Sistema de Registro Nacional de Emissões (National Emissions Registration System, SIRENE)⁴ and integrating efforts, particularly with MAPA, Ministério do Desenvolvimento Agrário e Agricultura Familiar (the Ministry of Agrarian Development and Family Farming, MDA), Ministério da Pesca e Aquicultura (the Ministry of Fisheries and Aquaculture, MPA), and the private sector. This national system must include strategic partnerships, training of technicians, and engagement with society in order to guarantee the legitimacy and effectiveness of the proposed improvements.

⁴ Available at: <http://sirene.mctic.gov.br>

Expected benefits and integration with the productive sector

Implementing a monitoring and inventory plan in the medium and long term will bring concrete benefits to Brazil, for several reasons. First, it will increase the reliability of the national inventory, permitting more accurate reports that adhere to tropical conditions, which strengthens the country's credibility in the UNFCCC. Second, it will improve the competitiveness of Brazilian agricultural products on the international market, meeting demands for traceability and a low carbon footprint such as those imposed by the European Union. Third, it will provide sensitive information for the productive sector, to guide public policies and investments in sustainability. Finally, it will promote international cooperation, positioning Brazil as a model for other tropical countries.

Integration with the private sector is an essential pillar of this plan, since producers not only provide primary data, but use technologies such as climate risk zoning (ZARC) and TerraClass, which are already demonstrating an impact on risk management and transparency. Meanwhile, MAPA's involvement ensures a connection between science and agricultural policy, while MCTI, as the national authority, coordinates the interface with the UNFCCC. This three-pronged connection between government, research, and the productive sector is the basis for the proposed monitoring infrastructure, ensuring that advances in the inventory reflect national and global priorities.

Table 7.2 shows a comparative analysis of the improvements between the 1996 and 2006 IPCC guidelines.

Characterization of uncertainties and limitations of current data

Brazil's tropical production systems are known for their wide diversity, ranging from extensive pastures in the Cerrado to irrigated rice crops in the South and integrated systems in the Amazon. Such heterogeneity represents a significant economic advantage, but also poses substantial challenges to accurate quantification of GHG emissions. The 2006 IPCC guidelines, adopted in the 2024 BTR, provide a methodological framework for assessing uncertainties in activity data (such as cattle herd size) and emission factors (like methane emissions per animal). However, applying these guidelines in tropical environments, which are characterized by dynamic soils and intense biological processes, reveals limitations that require adapted solutions.

Within the context of the BTR, Brazil has made progress in detailing the uncertainties associated with the agricultural sector, one of the main sources of national emissions. Enteric fermentation in cattle, for example, is a significant source of methane (CH_4), with values that vary according to climatic conditions and pasture types. The report estimates that activity data, such as the number of head of cattle, presents relatively low uncertainties, between 5 and 15%, thanks to statistical sources such as Instituto Brasileiro de Geografia e Estatística (the Brazilian Institute of Geography and Statistics, IBGE). However, emission factors vary considerably, from 20 to 50%, due to regional differences in pasture characteristics and the influences of the tropical climate.

Emissions of nitrous oxide (N_2O) from managed soils represent another critical challenge. In the tropics, high temperature and humidity conditions accelerate the release of this gas, especially in areas with intensive use of nitrogen fertilizers. The BTR recognizes that

Table 7.2. Comparative analysis of improvements between the 1996 and 2006 IPCC guidelines.

Approach	1996	2006
Scope and structure of agricultural emissions	The revised 1996 guidelines mainly dealt with agricultural emissions in a single chapter (Chapter 4: Agriculture), focusing on direct emissions from agricultural soils (such as nitrous oxide [N ₂ O] from the use of fertilizers, and methane [CH ₄] from enteric fermentation and manure management). Indirect emissions and emissions from land use change were addressed separately or less comprehensively, often in the sections on land use change and forestry (LUCF).	The 2006 guidelines introduced a more integrated framework, combining agriculture, forestry and other land uses into a single sector (AFOLU), covered in Volume 4. This restructuring reflects a holistic approach to land-based emissions and removals, recognizing the interconnections between agricultural activities and land use and management practices. Emissions from livestock, soil, and biomass burning are systematically linked to land use categories.
Refining the tiered approach	The three-tiered approach was present, but with less detail. Tier 1 relied heavily on standard emission factors and simplified activity data, with limited guidance for Tiers 2 and 3, which required country- and model-specific data. Focus on basic methods suitable for countries with limited data.	The tiered approach has been significantly refined and expanded. Tier 1 still uses standard emission factors, but with updated values based on more recent scientific data. Tier 2 incorporates specific emission factors by region or country and stratified activity data, offering greater precision. Tier 3 encourages the use of advanced models and measurements adapted to local conditions. The guidelines provide more detailed guidance and examples for implementing higher levels, especially for complex agricultural systems.
Enteric fermentation (CH ₄)	Methane emissions from enteric fermentation are estimated based on standard Tier 1 emission factors, which are determined by livestock categories (such as dairy cows, beef cattle, and sheep). These emission factors are uniform across large regions, and take aspects such as diet or management practices into account.	The methodology improves the estimation of CH ₄ from enteric fermentation by refining the emission factors and expanding the Tier 2 approach. It incorporates factors such as feed digestibility, animal productivity, and management systems (for instance, pasture vs. feedlot). This allows for more accurate estimates that reflect local conditions, with detailed guidance on collecting activity data, such as feed consumption.
Manure management (CH ₄ and N ₂ O)	Emissions from manure management were calculated separately for CH ₄ and N ₂ O, but the methodology used was simpler. The emissions of CH ₄ depended on standard factors linked to the type of livestock and broad climate zones, while N ₂ O emissions were estimated only for manure applied to the soil, with little attention paid to emissions during storage or handling.	The guidelines offer a more comprehensive approach to manure management. CH ₄ emissions are calculated based on volatile solids, methane conversion factors (MCFs), and specific management systems (such as anaerobic lagoons, composting, or solid storage), with updated MCFs reflecting climate and system variability. The N ₂ O emissions take into account direct emissions (from storage and treatment) and indirect emissions (like volatilization and leaching), offering a more complete view of the nitrogen cycle.
Agricultural soils (N ₂ O)	The emissions of N ₂ O from agricultural soils were mainly concentrated in direct emissions from synthetic fertilizers, organic additives (like manure), and crop residues. Indirect emissions (such as those resulting from leaching or atmospheric deposition) were recognized, but calculated using a simplified methodology and limited standard factors (such as a fixed fraction of nitrogen lost through leaching).	The guidelines improve estimation of N ₂ O emissions from soils by distinguishing more clearly between direct and indirect pathways. Direct emissions of N ₂ O include additional sources, such as urine and feces from grazing animals, with refined emission factors. Indirect emissions of N ₂ O are divided into two components: (1) volatilization of ammonia and NO _x , followed by redeposition, and (2) leaching/runoff of nitrogen into bodies of water. The methodology uses updated standard factors and encourages country-specific data for greater accuracy.

Continued...

Table 7.2. Continuation.

Approach	1996	2006
Rice cultivation (CH ₄)	Emissions of CH ₄ from rice cultivation used standard seasonal emission factors, which only take into account ecosystem type, standard waterlogging of the soil before and/or during the rice cultivation period, and the amount of organic material added to the soil.	The guidelines improved the estimates of CH ₄ emissions from rice cultivation, incorporating daily emission factors that consider the length of the cultivation period, as well as stratified scale factors for water regimes during and prior to cultivation, soil preparation systems, and types and quantities of organic material added to the soil.
Burning agricultural waste	Emissions from burning agricultural waste (CH ₄ , N ₂ O, and other gases) previously were covered briefly, with basic standard factors and little guidance on collecting activity data. This category was often optional for reports.	The guidelines provide a dedicated methodology for biomass burning within the AFOLU sector, including waste burning. They offer detailed standard emission factors for CH ₄ , N ₂ O, CO and NO _x , and encourage estimation based on the amount of biomass burned, combustion efficiency, and local practices, improving consistency with other land use burning estimates.
Data and uncertainty management	Uncertainty was recognized, but the guidelines for quantifying it were minimal. Standard emission factors had broad uncertainty ranges, and there was little emphasis on quality assurance/quality control (QA/QC).	The guidelines place greater emphasis on assessing and managing uncertainty, providing tools to quantify uncertainty at each stage (such as activity data and emission factors). They include detailed QA/QC procedures, and good practice guidelines to increase the reliability of agricultural emissions estimates.
Integration of indirect emissions	Indirect emissions (from leaching or volatilization, for example) were included but treated less rigorously, often through a single aggregate factor, and were not consistently linked to agricultural activities.	Indirect emissions have been integrated more systematically into the agricultural subsector. The methodology explicitly considers nitrogen losses through volatilization, leaching and runoff, using updated fractions and emission factors based on the latest research, which guarantees a more complete accounting of the nitrogen cycle.

the uncertainties in these estimates can be as high as 70%, due to the lack of detailed local measurements for different crops like soybeans and corn. In temperate regions soil processes are more predictable, but in Brazil, tropical variability requires a more specific approach based on regional data.

The 2006 IPCC guidelines call for implementation of quality assurance and quality control (QA/QC) procedures to ensure the consistency and reliability of estimates. In the BTR, Brazil describes the application of such procedures, including the cross-validation of activity data with independent sources, such as MAPA. In tropical systems, however, where practices such as no-till farming and ICLF influence soil carbon stocks, the reliance

on generic emission factors (like Tier 1) compromises the accuracy of estimates.

The tropical climate, characterized by high temperature and humidity, intensifies microbial activity in soils, affecting both CO₂ emissions and carbon sequestration capacity. The BTR uses Tier 1 methods for these estimates, but these approaches do not adequately capture the accelerated dynamics of tropical soils. The transition to Tier 2, with emission factors adjusted to the Brazilian context, as observed in part of the livestock sector, partially reduces uncertainties, but the absence of a comprehensive national monitoring infrastructure limits the extent of these advances.

The cultivation of irrigated rice, which is predominant in the south of the country and expanding in the north, exemplifies another

challenging aspect. These flooded areas have significant CH₄ production by methanogenic bacteria, but the BTR indicates high uncertainties due to variability in flooding periods and local climatic conditions. In contrast to temperate countries, where these processes are more stable, Brazil's tropical environment requires specific measurements to improve estimates.

The extensive livestock farming widely practiced in the Midwest also has tropical characteristics. Pasture quality is influenced by seasonal rainfall and alters enteric CH₄ emissions, but the BTR uses only partially adjusted emission factors. In the tropics, the rapid cycle of pasture growth and degradation differs markedly from conditions in temperate regions, requiring local studies that are still in their early stages (Cabral et al., 2024).

Tropical soils are often nutrient-poor and depend on fertilizers to sustain agricultural productivity, but the intense rainfall characteristic of tropical climates promotes nitrogen leaching, increasing indirect emissions of N₂O emissions (Swails et al., 2021). The BTR recognizes the lack of regional data to quantify this process, which results in less accurate estimates compared to countries with advanced monitoring networks.

Integrated systems like ICLF are typical of tropical Brazil and offer potential for carbon sequestration, but their contribution is underestimated in the BTR due to the lack of adapted models. In the tropics, the accelerated growth of trees and complex interactions between the components of the system require specific approaches that differ from those recommended by the IPCC for generic contexts (Costa et al., 2022).

For example, the high humidity of the tropics, especially in regions like the Amazon, amplifies indirect emissions of N₂O emissions through leaching (Pérez et al., 2000). The BTR uses standard IPCC factors, underestimating this impact compared to local measurements, which would be more appropriate for the regional hydrological regime. This limitation highlights

the need for investment in research focused on tropical conditions.

The heat-driven accelerated decomposition of animal waste in the tropics is another source of CH₄ and N₂O that the BTR does not quantify precisely. While countries like New Zealand use direct measurements for these processes, Brazil still relies on global averages, compromising the representativeness of estimates in the tropical context.

Meanwhile, the diversity of tropical crops such as sugar cane, coffee, and soybeans introduces additional complexity. Each crop interacts differently with the soil, but the BTR aggregates these emissions into broad categories, unlike developed countries that disaggregate the data by type of crop and climate. This generalization reflects the lack of a detailed data collection infrastructure.

The 2024 BTR represents significant progress in identifying these gaps and proposing improvements. In the tropics, the intense dynamics of soils and climate demand continuous monitoring based on local measurements, rather than relying exclusively on secondary data or global assumptions.

Compared to temperate countries, Brazil faces a structural challenge due to the high variability of its tropical systems. The 2006 guidelines provide a solid basis, but they were not designed to fully capture these specificities, which reinforces the need for an adapted approach under the proposed plan.

The characterization of the national agricultural inventory in Brazil, using the 2006 IPCC method, faces specific challenges due to the particularities of tropical systems, such as:

- High climate variability, with unpredictable rainfall patterns and more frequent extreme events, which affect the dynamics of emissions.
- The diversity of tropical soils, many of which are highly sensitive to organic decomposition, requires adjustments to emission factors.

- The predominance of integrated systems, such as the ICLF, which are not fully included in the traditional IPCC categories.
- The specificities of tropical livestock farming, including diets based on native pastures and the physiological adaptations of cattle to hot climates.
- The need to incorporate local agricultural practices, such as controlled burns and management of secondary vegetation, which have different impacts on carbon stocks.

These specific characteristics require methodological adaptations to ensure accuracy in the inventory. Finally, reducing uncertainty in the tropical agricultural sector requires an approach that extends beyond the mere adoption of international methods. The medium- and long-term plans should prioritize the generation of local data, development of models adjusted to the Brazilian climate, and implementation of a monitoring infrastructure that reflects the reality of tropical agricultural production systems.

Comparative analysis between sectors

Brazilian agriculture, with its tropical systems, stands out in the 2024 BTR as one of the sectors with the greatest uncertainty, but it is not alone. The energy, industrial processes and product use (IPPU), waste and land use, land use change, and forestry (LULUCF) sectors also face specific challenges, permitting a comparative analysis that clarifies unique tropical characteristics and guides the proposed monitoring plan. This section examines the differences between these sectors, focusing on the implications for agriculture summarized in Table 7.3.

In the energy sector, which includes sources such as thermal power plants and fossil fuels, the estimates show reduced uncertainties that

vary from 5 to 10%. The BTR highlights the reliability of activity data obtained from official records, such as fuel consumption. In the tropics, climatic conditions have little effect on industrial processes; this is different from agriculture, where uncertainty can reach 20–70% due to the direct influence of climate on biological systems, which are highly sensitive to climatic variables (precipitation, temperature and humidity), in turn increasing variability in methane (CH₄) and nitrous oxide (N₂O) emissions (IPCC, 2019).

The biological nature of farming is a determining factor in its uncertainties. Enteric CH₄ emissions, for example, depend on the cattle's diet, which in turn is influenced by seasonal rainfall, while processes in the energy sector are mechanical and predictable. The BTR reflects this difference, highlighting the need for local data to capture tropical variations.

In the energy sector, data consistency is ensured by centralized records, while in the agricultural sector the BTR uses cross-validations between IBGE and MAPA, a QA/QC effort that partially reduces errors. However, tropical conditions require more detailed data collection, which is still under development.

The IPPU sector, which includes industries such as cement and chemicals, is also moderately uncertain, between 10 and 20%. Industrial processes are largely standardized, and production data is well documented, as indicated in the BTR. In the tropics, climate impacts are limited to logistical aspects such as transportation, while in the agricultural sector, biological and environmental variability introduces significantly more complexity.

Emissions of N₂O in the agricultural sector from the fertilizer use are particularly sensitive to tropical conditions of heat and humidity, in contrast to the IPPU sector, where N₂O is generated in controlled processes. The BTR notes that while industry uses direct measurements,

Table 7.3. Comparison between the agricultural sector and other sectors in the 2024 BTR.

Aspect	Agriculture and livestock production	Energy	IPPU	Waste	LULUCF
Uncertainty (%)	20-70% (greater variability)	5-10% (low uncertainty)	10-20% (moderate uncertainty)	20-50% (high variability)	20-100% (largest uncertainty range)
Data source	Scattered data (IBGE, MAPA), cross-validation	Centralized records (fuel consumption, energy production)	Standardized industrial data (chemical production, cement)	Urban data (landfills, effluents), but with rural gaps	Remote sensing (PRODES), but variable emission factors
Tropical Influence	High (climate affects biological emissions: Enteric CH ₄ , N ₂ O from the soil)	Low (industrial processes little affected)	Moderate (indirect impacts, such as logistics)	High (accelerated decomposition of organic matter in hot climates)	Extremely high (deforestation, fires, change in land use)
Complexity	Open systems, dependent on climate, soil and animal/vegetable biology	Mechanical/controlled processes, predictable	Closed, monitored industrial processes	Mixture of urban (more controlled) and rural (less monitored) sources	Land use dynamics, interaction with agriculture
IPCC method	Tier 1 (predominant) and Tier 2 (partial livestock)	Tier 1 and 2 (precise data)	Tier 1 and 2 (detail by industry)	Tier 1 and 2 (depending on the quality of the activity data)	Tier 2/3 (remote sensing, but generic tropical factors)
Main Challenges	Lack of local data, emission factors not adapted to tropical systems	Lower priority for tropical monitoring	Low direct climatic influence	Inconsistent data in rural areas and accelerated decomposition	Variable emission factors in tropical biomes
BTR Recommendations	Specific data collection, adapted models, reduced dependence on Tier 1	Maintain consolidated systems	Improve data on specific chemical processes	Improve monitoring of rural waste and effluents	Integrate remote sensing with local data

agriculture depends on generic factors, which increases uncertainty in tropical soils.

IPPU benefits from closed and monitored processes, in contrast to agriculture, where open systems are influenced by unpredictable climatic and biological variables. The BTR uses Tier 2 for some agricultural categories, such as livestock, but for soils and manure it still relies on Tier 1, reflecting the lack of specific tropical data.

The waste sector, which includes emissions from landfills and effluent treatment, has uncertainties comparable to those in the agricultural sector, ranging from 20 to 50%. The tropical climate accelerates decomposition of organic matter, increasing CH₄ emissions, but activity data (such as the volume of waste disposed) lacks precision. In the agricultural sector, the dispersal of animal waste in extensive

tropical systems exacerbates this challenge, requiring different approaches.

In the waste sector, decomposition accelerated by the tropical climate is similar to that observed in the agricultural sector, especially in the management of animal waste. However, the BTR indicates greater precision in urban waste data compared to rural data, where geographical dispersion makes monitoring difficult. This distinction underlines the need for a specific infrastructure for the tropical agricultural sector.

The similarity between the waste and agricultural sectors lies in the influence of the tropical climate on organic decomposition. But while waste is concentrated in urban areas, the agricultural sector covers vast rural areas, making it difficult to apply uniform methods. The BTR recognizes this limitation, and suggests improvements in data collection.

The LULUCF sector, which is responsible for emissions associated with land use and forests, has the greatest uncertainties, ranging from 20 to 100%. In the tropics, deforestation motivated by real estate speculation or agricultural expansion and naturally occurring fires create a complex dynamic, as detailed in the BTR. Although deforestation data is accurate, thanks to tools such as Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite (the Project for Monitoring Deforestation in the Legal Amazon by Satellite, PRODES), emission factors vary widely due to the diversity of biomes, a challenge that is also reflected in estimates for the agricultural sector.

The intersection between the LULUCF and agricultural sectors in the tropics is evident, since many pasture areas are derived from cleared forests. BTR attempts to separate soil carbon emissions from CH₄ emissions from livestock, but the Tier 1 models used do not adequately reflect this complex interaction, increasing uncertainties in both sectors.

The LULUCF sector uses advanced technologies like remote sensing to monitor deforestation, but the emission factors remain uncertain in the tropics. Meanwhile, in the agricultural sector, BTR depends on less precise maps for livestock and soil management, which indicates the need to integrate similar tools into the monitoring plan.

Comparative analysis reveals that the tropical agricultural sector is the most dynamic and uncertain, due to its dependence on biological processes strongly influenced by the climate. While the energy and IPPU sectors are more stable, the monitoring plan should prioritize agriculture, with adaptations to the tropical conditions that characterize it.

Finally, the BTR suggests that reducing uncertainties in the agricultural sector requires local data and models adjusted to tropical particularities. In the other sectors progress is more linear, but in agriculture the plan must tackle biological and climatic complexity, ensuring a specific and robust approach.

The forest degradation dichotomy

The relationship between tropical production systems and forests is intrinsic in Brazil, and the 2024 BTR addresses this interaction via the dichotomy “forest degradation due to human activity versus degradation due to natural losses from forest fires and ecosystem dynamics.” This duality is essential for the monitoring plan, since anthropogenic actions and natural processes intertwine in the tropics, intensifying their effects and impacts, especially in ecotone regions such as the Cerrado and the Amazon, as well as transitions between other biomes like the Caatinga, Pantanal, Atlantic Forest and Pampa (Pellegrini et al., 2023).

Forest degradation driven by human activities, such as deforestation for real estate speculation or agricultural expansion, is the main source of emissions in the LULUCF sector (Assunção et al., 2023). The BTR estimates that these activities generated approximately 1.2 Gt of CO₂ equivalent in 2020, with significant carbon losses in biomes such as the Amazon and Cerrado. In the tropics, conversion of forests into pastures occurs rapidly, and exposed soils release carbon at higher rates than in temperate regions.

Tropical soils that lose their forest cover become rapid sources of CO₂, especially in ecotones where vegetation transitions are abrupt. The BTR recognizes that current models underestimate these impacts, since the tropical climate speeds up decomposition compared to temperate regions and requires specific methodological adjustments.

The agricultural sector is directly linked to this binomial, since many areas degraded by anthropogenic action are converted into pastures or crops. The BTR attempts to quantify enteric CH₄ emissions from livestock and soil carbon in these areas, but the IPCC's generic models do not fully capture tropical complexity, resulting in high uncertainties that the monitoring plan must address.

Activity data for anthropogenic degradation obtained by remote sensing (such as those from PRODES) have relatively low uncertainties of between 5 and 15% (Almeida et al., 2023). But as mentioned earlier, the emission factors that estimate the carbon released by different types of vegetation and tropical soils vary from 20 to 100%, due to ecological diversity and the lack of detailed local measurements, as recorded in the BTR.

Anthropogenic degradation predominates as a source of emissions in the LULUCF category, but natural degradation is gaining relevance due to climate change. Natural degradation, resulting from spontaneous forest fires and ecosystem

processes, has less impact but is not negligible. In the tropics, hot and dry conditions favor biomass combustion, especially during climatic events such as El Niño (Aragão et al., 2018). The BTR highlights the difficulty of distinguishing natural causes from those amplified by human actions, since both coexist and feed back into each other in tropical environments. The report also identifies ecotones as critical areas that require greater attention in the monitoring plan.

Natural degradation, monitored using satellite images by Instituto Nacional de Pesquisas Espaciais (the National Institute for Space Research, INPE), presents moderate uncertainties in the activity data (10–20%), but the emission factors associated with fires vary between 20 and 50% (Aguiar et al., 2012). In the tropics, fire intensity and vegetation composition differ between biomes, and the BTR points out that in ecotones, these uncertainties increase due to the lack of specific data.

Human activity amplifies natural processes in the tropics, as evidenced by the BTR. Deforestation leaves behind dry biomass, which serves as fuel for fires, a phenomenon that is less common in cold climates. The monitoring plan must take this synergy into account, prioritizing strategies that reduce anthropogenic emissions while mitigating exacerbated natural impacts. In ecotone regions, the interaction between the two factors is particularly pronounced. The BTR points out that deforestation creates vulnerable forest edges, which are more susceptible to fires due to the reduction in local humidity. In the tropics, this process is aggravated by the hot climate, which intensifies degradation in a vicious cycle, unlike temperate ecosystems where these dynamics are less severe.

Tropical heat makes natural fires more intense than in temperate forests, and the BTR points to the need for granular data to capture this dynamic in ecotones. Integration of the agricultural sector in these areas requires an

approach that combines remote sensing with local measurements. Natural fires in the Cerrado, which are part of the dynamics of this ecosystem, become more severe with prolonged droughts, which in turn are intensified by climate change. The BTR points out that this deterioration exceeds the capacity for natural regeneration, a challenge that the plan must address with management strategies adapted to tropical conditions.

The natural regeneration of secondary forests, however, offers the potential to remove CO₂ removal, but the BTR estimates uncertainties of 30–70% due to the variability of plant growth in the tropics. Agriculture can contribute through systems like ICLF, but the lack of precise measurements limits the inclusion of these benefits in inventories. Mitigating anthropogenic degradation, such as controlling illegal deforestation, is a priority according to the BTR; however, managing natural degradation with activities like restoring ecotones is also essential. In the tropics, the plan must address both aspects in an integrated manner, reflecting the interdependence between the factors.

Finally, the tropical agricultural sector operates in this interconnected context, with pastures replacing forests and soils that are highly sensitive to the climate. The BTR highlights the challenges of quantification, and the monitoring plan must develop an infrastructure that takes this reality into account, capturing emissions and removals in a holistic way that is adapted to the tropical environment.

Proposals for refinements

The specific characteristics of Brazil's tropical systems make the agricultural sector a unique challenge in the BTR. However, comparisons with developed countries such as the United States,

New Zealand and nations in the European Union offer valuable lessons. These countries reduce their uncertainties with advanced infrastructure and adjusted methods, and the medium- and long-term plans can adapt these practices to the tropical context, strengthening the national inventory and Brazilian competitiveness.

In the United States, the Daycent model estimates N₂O emissions in soils with uncertainties reduced to around 10%, using local climate and management data. In Brazil, BTR still depends on Tier 1 methodologies for this category, with uncertainties of up to 70%. In the tropics, accelerated soil dynamics require models adapted to the local heat and rainfall, a priority for the proposed plan.

The European Union centralizes agricultural data on the Eurostat platform, and uses satellites such as Sentinel for monitoring. In Brazil, although PRODES serves the LULUCF sector, agricultural monitoring depends on sources such as IBGE, which lack granularity. The plan should establish a national tropical data network, integrating remote sensing and field measurements.

In New Zealand, enteric CH₄ emissions are measured directly with flow chambers, reducing uncertainties to 15%. In the Brazilian tropics, where pastures vary seasonally, the BTR estimates uncertainties of 20 to 50%. The plan could implement similar technologies, adapted to tropical conditions, to improve accuracy.

While developed countries make significant investments in research and infrastructure, Brazil moves forward with limited resources. The BTR already uses Tier 2 methodologies for livestock, but the soil and manure categories remain in Tier 1. The plan should seek ongoing funding, possibly with international support such as that offered by the Global Environment Facility (GEF), to support detailed tropical measurements.

The tropical climate intensifies N₂O and CH₄ compared to temperate regions. The BTR tries

to promote adjustments, but the IPCC models were not designed for this purpose. In the United States, the models are calibrated locally; the Brazilian plan should follow suit, adapting tools like Century for specific biomes like the Cerrado.

The European Union ensures consistency between member countries, while Brazil with its continent-spanning size requires a regionalized approach. The BTR still aggregates data broadly, but the plan could make progress in developing specific inventories by biome, capturing tropical variations between the Amazon, Cerrado, and Southern region.

New Zealand aligns its agricultural policies with climate goals, adjusting incentives based on accurate data. In Brazil, the ABC+ Plan⁵ promotes sustainable practices, but the BTR still lacks detailed indicators. The monitoring plan must integrate these policies, quantifying the benefits of ICLF systems in the tropics, for example.

In the United States, rural extension programs train producers to collect data, while in tropical Brazil access to such tools is limited. The plan could include training farmers to adopt IPCC methodologies and protocols, expanding the database on emissions and removals in tropical systems.

Tropical soils have the potential to sequester carbon through ICLF systems (Vogado et al., 2024), but the BTR underestimates this benefit. In temperate countries, carbon in the soil is more stable, while in the tropics the cycle is faster (Lal, 2008). The plan is to invest in sensors and models that capture these specific dynamics.

Intense tropical rainfall increases indirect emissions of N₂O by leaching (Hey et al., 2025), but the BTR still uses generic factors. The European Union carries out direct measurements of this process. The Brazilian plan is to install

sensor networks in crops such as coffee and soybeans, reflecting local conditions.

New Zealand adds value to its meat with accurate emissions data, a model that could be applied to tropical Brazil. The plan could detail breeds and pastures, strengthening competitiveness in the global market with sustainable farming adapted to the hot climate.

In the United States, the integration of satellites and sensors reduces uncertainty. In Brazil, this role has been played by INPE, but Brazilian agriculture presents complex challenges and demands, given its size and the diversity of biomes and climates. The plan should be based on a platform that integrates efforts aimed at the agricultural sector, such as Embrapa's Integra Carbono initiative⁶ (Figure 7.1), which could be interoperable with MCTI's SIRENE to consolidate tropical data.

Tropical conditions are a challenge, but also represent an opportunity. Although the BTR shows progress, the plan must go further, with an infrastructure that translates the reality of the agricultural environment into reliable figures, positioning Brazil as a leader in tropical sustainability.

The 2025 United Nations Climate Change Conference (COP30) will be a showcase for this plan. With reduced uncertainties and robust data, Brazil can demonstrate that the tropical agricultural sector is a global example, supported by the collaboration between Embrapa and MCTI and by a vision adapted to its specific characteristics.

⁵ Available at: <https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/planoabc-abcmais>

⁶ Launched on Embrapa's anniversary in 2024, this initiative aims to gradually integrate the efforts of Embrapa and partner institutions (both public and private) on the subject of climate change and agriculture, in terms of both carbon balance and methods and indicators for adaptation, resilience, and sustainability of agricultural, livestock, and forestry systems and their integrations.



Figure 7.1. Launched on the anniversary of Embrapa in 2024, this initiative is intended to integrate efforts by Embrapa and partnering public and private institutions on the topic of climate change and agriculture in a gradually evolving manner, in terms of carbon balance as well as methods and indicators for adaptation, resilience and sustainability of systems involving agriculture, ranching, forests and integrations.

Source: Embrapa (2025).

Innovation solutions

As highlighted in the previous sections, transparency is a fundamental pillar of the multilateral climate change regime within the United Nations. The focus is on establishing transparent metrics that are capable of ensuring comparability between countries in a complete, consistent, and accurate manner.

This pillar is structural and, in this sense has the support of the IPCC, which has produced and revised methodological guidelines over the years to guide countries in developing, monitoring, and verifying estimates of GHG emissions and removals. The Paris Agreement currently uses the 2006 IPCC guidelines for drawing up the BTRs, with the possibility of using the methodological improvements published in 2019 if the country deems it appropriate.

From the start of the process of building the guidelines, transparency was addressed by the UNFCCC as a fundamental pillar. This was originally structured in preparatory documents, and later detailed in the 1996 IPCC guidelines in the form of five components: Transparency, Accuracy, Comparability, Completeness and Consistency. These components were used to classify the technological solutions presented in this section, based on the following definitions:

Transparency: refers to the clarity and accessibility of the information, allowing the methods, data, and assumptions used in the estimates to be understandable and verifiable by third parties.

Accuracy: seeks to minimize uncertainties and errors, providing estimates that are as close as possible to the real values, based on reliable data and robust methods.

Comparability: ensures that data and methods are consistent between countries or periods, allowing fair and standardized comparisons.

Completeness: ensures that all relevant sources of emissions and removals are included, covering all necessary sectors and gases.

Consistency: refers to the uniformity of methods and data over time, avoiding unjustified discrepancies in the time series.

The transparency regime refers to this set of characteristics, called TACCC, which, over the last few decades, has led to the development of tools and methodological packages to ensure that countries can inventory the emissions that are inherent in their economic processes. These improvements allow the use of simplified methods while simultaneously offering opportunities to invest in the sophistication of methodologies to ensure the precise characterization of the particularities, practices, and processes that are typical of the local environment, as well as social and economic characteristics.

The following are ten innovation solutions developed by Embrapa and its many partners, cataloged and classified according to their alignment with the TACCC principles.

Solution 1 – TerraClass

The TerraClass technology, developed to map and monitor land use in Brazil (particularly in deforested areas), offers significant practical benefits for society and can contribute to increasing transparency in the national GHG inventory. Improving adoption of this technology will expand the national capacity to use remote sensing information and geospatial analysis. In this way, TerraClass provides detailed insights into post-deforestation land use (such as agriculture, pasture, or natural regeneration), allowing precise tracking of land management practices in tropical agricultural systems.

This capacity strengthens Brazil's compliance with international climate commitments, such as the Paris Agreement's Nationally Determined Contribution (NDC), by supporting the development of Tier 3 emissions estimates for the LULUCF sector.

During the technical analysis of the BTR, as established in the modalities, procedures, and guidelines (MPGs) of the Paris Agreement, the TerraClass technology can be presented as a domestic effort to generate robust data and use information for management and evidence-based decision making. In this way, it will favor national initiatives to formulate policies that support a more accurate understanding of Brazil's emissions reduction trajectory, providing consistent and transparent data on the dynamics of carbon flow in agricultural systems. For society, the TerraClass technology promotes sustainable land use, supports food security by optimizing agricultural areas, and reinforces Brazil's credibility in global markets, in line with regulations such as the European Union Deforestation Regulation (EUDR). By increasing product traceability and resilience to the impacts of climate change, TerraClass consolidates Brazil's leadership in sustainable tropical agriculture and global climate action.

How this solution contributes to national competitiveness

TerraClass strengthens Brazil's competitiveness on the global stage by providing a reliable and transparent basis for monitoring land use, which is essential in a context of growing international pressure for sustainability and traceability in agricultural production chains:

- Certification and access to international markets: the maps generated by TerraClass have the potential to contribute to the national effort to demonstrate effective compliance with climate commitments, like the NDC of the Paris Agreement, as well as to meet the demands of markets such

as the European Union, which implements regulations such as the EUDR that require deforestation-free products. This increases the value of Brazilian commodities like soybeans, meat, and timber, increasing their acceptance and competitiveness.

- **Attracting investments:** the transparency provided by TerraClass, in line with the 2006 IPCC guidelines, increases Brazil's credibility in reports such as the BTR, attracting climate finance and green investments from international institutions and private funds interested in supporting countries with sustainable practices.
- **Efficient land management:** by identifying post-deforestation land use (for example, agriculture, livestock and regeneration), TerraClass supports public policies and private sector strategies to optimize the use of areas that have already been cleared, reducing the costs of expanding the agricultural frontier and reinforcing Brazil's position as a leader in sustainable tropical agriculture.

How this solution reduces exposure to risk and increases adaptive capacity

TerraClass plays a crucial role in mitigating climate and socio-economic risks, while strengthening the resilience of the Brazilian agricultural sector in the face of climate change:

- **Reducing regulatory and trade risks:** the ability to monitor and report land use accurately reduces the risk of trade sanctions or barriers imposed by importing countries that demand guarantees against illegal deforestation. The technical and scientific robustness associated with the data produced by innovation solutions of this nature protects Brazilian agribusiness, safeguards small Brazilian producers, and contributes to a favorable business environment, and obviously fosters food safety, income for small producers, and the sustainability attributes of Brazilian agricultural production.

- **Prevention of environmental disasters:** by mapping deforested areas and their uses, TerraClass makes it possible to identify regions vulnerable to degradation (such as erosion and loss of fertility), permitting preventive interventions such as the recovery of degraded areas or adoption of agroforestry systems, which increase the resilience of the soil and ecosystems.
- **Adaptive capacity:** TerraClass data helps guide agricultural planning, adjusting land use to climatic conditions and projections of future changes (for example, droughts in the Cerrado or intense rainfall in the Amazon). This allows Brazil to adapt its production to climate variations, maintaining productivity in adverse scenarios.

How can society perceive and understand the strategic importance of the development of this solution

Effectively communicating the benefits of TerraClass can increase its acceptance and recognition by Brazilian and global society, highlighting its strategic relevance:

- **Education and awareness:** the availability of accessible and visual maps (via online platforms or public reports, for instance) can be used in educational campaigns to show how Brazil monitors and manages its biomes, promoting an image of environmental responsibility. This activity is particularly important amid growing concern about climate change among young people and consumers.
- **Community engagement:** for farmers and local communities, TerraClass can be presented as a tool that protects their livelihoods by preventing unsustainable land use. For the urban public, it can be associated with the preservation of ecosystem services

such as water and climate, which affect quality of life in cities.

- National leadership narrative: society can understand TerraClass as a symbol of Brazil's pioneering spirit in environmental monitoring technologies, reinforcing national pride and the perception that the country is leading global efforts against deforestation, regardless of the policies adopted by other nations.

Impact on the sustainability of food production in Brazil and worldwide

TerraClass has a direct impact on the sustainability of food production in Brazil, and also generates positive externalities on a global scale, consolidating the country's leadership in sustainable agricultural practices.

Direct impacts in Brazil

Efficient land use: by mapping deforested areas and their uses, TerraClass encourages sustainable intensification on land that is already cleared (for example, via ICLF or CLI systems), reducing the need for new deforestation and preserving the soil's productive capacity in the long term.

Food security: identification of areas suitable for agriculture or sustainable pasture guarantees continued production of essential foodstuffs (like soybeans, corn, and meat), meeting domestic demand and also supplying exports, which represent a significant portion of the Brazilian economy.

Emissions reduction: monitoring natural regeneration or agricultural use in deforested areas contributes to more accurate estimates of GHG emissions and removals in the land use sector (LULUCF), supporting national climate targets and low-carbon agriculture.

Global externalities

Replicable model: TerraClass, integrated into PRODES, is an example of monitoring technology

that can be adapted by other tropical countries with similar challenges, such as Indonesia or the Democratic Republic of Congo, increasing its impact on reducing global deforestation.

Contribution to the global climate:

preservation of biomes such as the Amazon and Cerrado, facilitated by TerraClass, benefits the world by maintaining preserved natural environments that influence rainfall patterns and microclimates, impacting agriculture in other regions (like South America and Africa).

Independent leadership: continued investment in TerraClass demonstrates that Brazil prioritizes sustainability, regardless of other countries' policies, positioning itself as a proactive leader in a global scenario of unequal climate action. This reinforces Brazil's influence in international negotiations, such as the COP, and in global supply chains.

Solution 2 – Agricultural Climate Risk Zoning

The ZARC (Agricultural Climate Risk Zoning) technology is a strategic tool that maps the best times and regions for planting in Brazil, promoting practical benefits for society and improving the transparency of the national emissions inventory. By indicating periods of lower climatic risk for crops such as soybeans, corn and wheat, ZARC reduces agricultural losses caused by droughts, heavy rains or frosts, guaranteeing food security, price stability and financial protection for producers, through programs such as PROAGRO and Seguro Rural (Rural Insurance).

This technology is based on a methodological framework for aggregating detailed agrometeorological data, which contributes to an accurate understanding of tropical agricultural systems and enables more robust estimates of GHG emissions and removals in the agricultural sector. This methodological tool represents an important source of data which, in the future,

could support the move towards Tier 3 of the IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, using ZARC to develop this methodological framework could contribute to an accurate understanding of the national emissions reduction trajectory by providing reliable data on sustainable agricultural practices. These include efficient use of resources and the adoption of advanced agronomic practices that favor environmental sustainability and forest regeneration.

For society, ZARC strengthens the resilience of the agricultural sector, promotes sustainability, and reinforces Brazil's leadership in climate-smart agriculture, in line with global requirements and favoring access to international markets.

How this solution contributes to national competitiveness

ZARC strengthens Brazil's position as a leader in sustainable agricultural production by providing a strategic tool that optimizes productivity and reduces losses, in line with global demands for efficiency and environmental responsibility:

- Increased production efficiency: by indicating the best times and regions for planting various crops, ZARC minimizes losses due to climatic events (droughts, frosts), reducing costs for farmers and increasing the supply of agricultural products on the domestic and foreign markets. This strengthens the competitiveness of Brazilian commodities such as soybeans, corn, and coffee on international markets.
- Support for agricultural insurance policies: Integrated with programs such as PROAGRO, PROAGRO Mais, and Subvenção ao Prêmio do Seguro Rural (the Rural Insurance Premium Subsidy Program, SR), ZARC reduces financial risk for producers and encourages

investments in the agricultural sector. This economic stability attracts domestic and foreign investors, strengthening the rural economy.

- International credibility: ZARC's transparency, based on detailed agrometeorological data and standardized methodology, is in line with the requirements of reports such as the BTR and the 2006 IPCC guidelines. This demonstrates Brazil's commitment to climate management, improving its reputation in international negotiations and facilitating access to demanding markets such as the European Union.

How this solution reduces exposure to risk and increases adaptive capacity

ZARC is essentially a climate risk management tool that boosts the Brazilian agricultural sector's resilience in the face of climate change and extreme events:

- Reducing agricultural losses: by mapping risk zones and recommending planting periods with a lower probability of adverse weather conditions, ZARC reduces producers' exposure to economic losses caused by droughts, excessive rainfall, or extreme temperatures. This is particularly relevant in vulnerable biomes such as the Cerrado and the Semi-Arid region.
- Increased adaptive capacity: ZARC enables proactive adjustments to agricultural planning, such as selecting more resilient crops or altering planting calendars according to climate projections. This flexibility is crucial for responding to long-term changes, such as the increased frequency of extreme events predicted by climate models.
- Mitigating financial risks: integration with agricultural insurance programs reduces farmers' economic vulnerability, guaranteeing compensation in the event of losses and

encouraging continued production even in adverse scenarios. This protects both small producers and large supply chains.

How can society perceive and understand the strategic importance of the development of this solution

Clearly communicating ZARC's benefits can expand its acceptance by society, highlighting its role in food security, the economy, and climate adaptation.

Connection with everyday life: for the urban public, ZARC can be presented as a tool that ensures the availability of essential foodstuffs (rice, beans, and corn, for example) at affordable prices, even in years of unfavorable weather. Educational campaigns can use practical examples, such as protecting against crop losses that affect supermarket supply.

Value for farmers: for farming communities, ZARC is a guarantee of subsistence and profitability, easily understood through training and practical demonstrations (like field days). Associating it with insurance programs reinforces its perception as a “shield” against unforeseen events.

Narrative of innovation and leadership: society can recognize ZARC as an example of Brazil's groundbreaking work in agricultural science, showing how the country uses technology to face global challenges. This can be highlighted in the media and at events such as the COP, promoting national pride and awareness of the importance of climate adaptation.

Impact on the sustainability of food production in Brazil and worldwide

ZARC has a direct impact on food security and agricultural sustainability in Brazil, with positive externalities that reverberate globally, demonstrating the country's leadership in resilient agricultural practices.

Direct impacts in Brazil

National food security: by reducing crop losses, ZARC guarantees the continuous production of basic foodstuffs, meeting demand from a population that exceeds 200 million and maintaining price stability in the domestic market.

Agricultural sustainability: ZARC encourages efficient use of resources (such as water and soil) by avoiding planting in periods or areas of high risk, helping to preserve soil fertility and reduce emissions associated with poorly planned agricultural practices (like excessive use of fuels or fertilizers).

Support for low-carbon agriculture: by optimizing the agricultural calendar, ZARC indirectly reduces GHG emissions related to replanting or losses that require more inputs, in line with the goals of the Agricultura de Baixa Emissão de Carbono (Low-Carbon Agriculture or ABC plan).

Global externalities

A model for other countries: ZARC is a technology that can be replicated in tropical or developing nations that face similar climate risks, such as India, Mexico or African countries. Its methodology can be adapted to local cultures, increasing its impact on global food security.

Contribution to the global climate: by increasing the resilience of Brazilian agricultural production, ZARC helps maintain Brazil's position as one of the largest exporters of food (such as soybeans, meat, and sugar), stabilizing global supply amid a scenario of climate change that threatens other producing regions.

Independent leadership in sustainability: ongoing investment in ZARC, which has evolved since its creation in the 1990s, demonstrates Brazil's commitment to sustainability, regardless of the policies of other countries. This positions the country as a leader in climate-smart

agriculture, influencing global standards and climate negotiations, such as the UNFCCC.

Solution 3 – PlanejArroz

The PlanejArroz technology is a software tool developed to optimize planning and decision making related to the various management practices for irrigated rice, as well as provide an estimate of crop productivity for Rio Grande do Sul, which accounts for around 70% of the country's production of this cereal grain.

The technology provides strategic support, by means of advanced tactical planning, helping to determine the most appropriate time to carry out the main crop management practices. It offers practical benefits to Brazilian society by increasing production efficiency, optimizing use of natural resources and inputs while also reducing losses and GHG emissions. In this way, it helps to ensure that activity data and emission factors reinforce the completeness and accuracy of the national emissions inventory.

By integrating climate and management data, PlanejArroz (Figure 7.2) guides irrigated rice producers in southern Brazil on the efficient use

of natural resources and inputs, such as water, fertilizers, chemical pesticides, and fuels, reducing costs and losses in the soil/plant system and ensuring a greater supply of rice in a sustainable manner. The technology facilitates crop planning and offers predictability to rice production in Rio Grande do Sul, contributing to food security. Its standardized data improves the understanding of agricultural systems, permitting more accurate estimates of GHG emissions in rice production, especially methane (CH₄), making it a strategic tool for generating robust data that reinforces the quality of emission factors and activity data which are essential for the Tier 2 level, according to IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, robust access to strategic information promoted by PlanejArroz will help clarify the trajectory toward reducing national emissions by enabling adoption of sustainable production practices, such as optimizing the use of natural resources and inputs, reflected in increased productivity.

For society, the technology contributes to sustainable production, minimizes susceptibility to climate risks, and positions Brazil as a leader in resilient agriculture, supporting the traceability demanded by global markets and climate negotiations.

How this solution contributes to national competitiveness

PlanejArroz increases the competitiveness of the Brazilian rice sector by optimizing production and aligning with global demands for efficiency and sustainability:

- Reducing costs and increasing efficiency: by optimizing the use of natural resources, inputs and fossil fuels and promoting efficient crop management, PlanejArroz reduces production costs, allowing producers to offer rice at more competitive prices on the domestic

Photo: Paulo Lanzetta

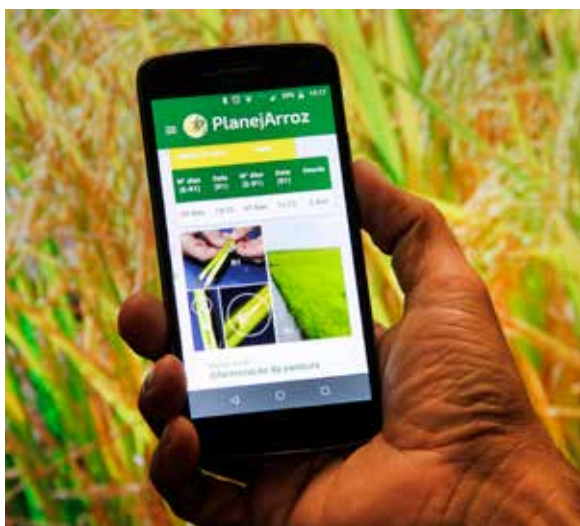


Figure 7.2. PlanejArroz software for planning management and estimating productivity in irrigated rice.

and foreign markets. This is crucial in a sector where Brazil competes with major exporters such as Thailand and Vietnam.

- Support for traceability and certification: PlanejArroz's ability to generate standardized data on management and productivity facilitates the certification of sustainable practices, meeting the requirements of international markets (such as low emission standards or efficient use of resources), which increases the value of Brazilian rice in global negotiations.
- Strengthening the image of agribusiness: the comparability provided by PlanejArroz, in line with the 2006 IPCC guidelines, reinforces Brazil's credibility in reports such as the BTR, highlighting its commitment to low-carbon agriculture and attracting international investments and partnerships.

How this solution reduces exposure to risk and increases adaptive capacity

PlanejArroz is a planning and management tool that lends predictability to production, and can minimize climatic and economic risks while increasing the resilience of irrigated rice production in the face of climate change:

- Reducing operational risks: the software helps with planning and choosing the right time to implement the best management practices, particularly nitrogen fertilization, increasing production efficiency and reducing exposure to losses due to adverse weather events.
- Adaptive planning: by estimating productivity based on climate and management data, PlanejArroz allows for real-time or seasonal adjustments, such as changing sowing times and the main management practices, as well as scaling them to the seasonal production potential, adapting production to climate variations and long-term projections (like

rising temperatures or changes in rainfall patterns).

- Economic stability: optimizing the use of resources and inputs, in addition to promoting production efficiency and increased profitability, allows secure investments compatible with projected returns, protecting producers against price fluctuations in the global market and supply crises, which is essential for the continuity of production in uncertain scenarios.

How can society perceive and understand the strategic importance of the development of this solution

Communicating the benefits of PlanejArroz as a planning and management tool highlights its relevance for production predictability and food security, making it more understandable and valued by society.

- Relevance to food security: for the general public, PlanejArroz can be presented as a tool that helps optimize production of rice (a staple of the Brazilian diet) even in challenging climatic conditions, connecting its development to the consumer's table.
- Direct benefit to producers: for farmers, PlanejArroz can be promoted as a practical application that enables efficient crop planning and management, reflected in investments that are compatible with production potential and, consequently, optimized economic returns.
- Symbol of sustainable innovation: society can understand PlanejArroz as part of the national research effort to lead in climate-smart agriculture, using technology for efficient, resilient, and sustainable production. This can be highlighted in media campaigns or events such as the COP, reinforcing the perception that Brazil invests in practical and sustainable solutions.

Impact on the sustainability of food production in Brazil and worldwide

PlanejArroz has a direct impact on the sustainability of rice production in Brazil, as well as generating positive global externalities, consolidating the country's leadership in resilient agriculture with a low environmental impact.

Direct impacts in Brazil

Efficient use of natural resources and inputs: promoting efficient use of natural resources (like water) and inputs (like fertilizers, chemical pesticides, and fossil fuels) results in the mitigation of GHG emissions associated with the cultivation of irrigated rice, which is a significant source of atmospheric methane (CH₄) emissions due to the fact that production takes place primarily on flooded soil. This is in line with the ABC+ Plan and the national climate targets.

Food security: by enabling proper crop management, the PlanejArroz technology contributes to increases in productivity and a reduction in losses. In this way, it ensures the domestic market a stable supply of rice, an essential component of the basic diet of millions of Brazilians. And if there are production surpluses, the country will be able to expand its share of the international market, especially when production is accompanied by environmental certification.

Environmental preservation: optimizing management practices reduces pressure to expand agricultural areas, helping to preserve biomes, particularly in lowlands of southern Brazil that are fundamental for ecosystem services (such as water regulation).

Global externalities

Replicable model: PlanejArroz can be adapted and extended to other irrigated rice producing countries, particularly in the Southern Cone of the Americas, which grow rice in similar climatic

and soil conditions to southern Brazil and face the same challenges related to methane emissions and climate change. Its methodology, based on climate and management data, is exportable, boosting its impact on global sustainability.

Contribution to the global climate: reducing emissions in the Brazilian rice sector benefits the world by mitigating global warming, while stability in rice production helps balance the food supply in a scenario where climate crises affect other regions.

Independent leadership: the development of PlanejArroz reflects Brazil's commitment to sustainable innovation, regardless of the policies of other countries. This positions the country as a leader in agricultural technologies that combine productivity and environmental responsibility, influencing global standards and climate negotiations.

PlanejArroz was developed in a partnership between Embrapa Temperate Agriculture, Instituto Rio-Grandense do Arroz (the Rio Grande do Sul Rice Institute, IRGA), the Federal University of Santa Maria (UFSM), and Instituto Nacional de Meteorologia (the National Meteorological Institute, INMET). The software is available on the web (planejarroz.cpact.embrapa.br) and also in iOS (available on the App Store) and Android (available on Google Play) versions.

Solution 4 – Soil Quality, Carbon Stock and Production in Different Farming Systems

The Qualidade de Solo, Estoque de Carbono, Produção em Diferentes Sistemas de Produção Agropecuários (Soil Quality, Carbon Stock and Production in Different Farming Systems) technology, which focuses on ICLF, offers practical benefits to society by improving physical models that quantify soil quality, carbon

stocks and productivity. This technology makes it possible to optimize the production of grains, meat, and wood in tropical areas, reducing costs and strengthening resilience against climatic disasters such as drought and erosion.

The detailed data contributes to a more accurate understanding of tropical agricultural systems, providing robust estimates of GHG emissions and removals in the agricultural sector in line with Tier 2 of the IPCC guidelines.

During the technical analysis of BTR, as defined by the MPGs of the Paris Agreement, this technology could be strategic in supporting assessment of the national emissions reduction trajectory, by demonstrating carbon sequestration in soils and biomass, as well as emissions mitigation through integrated practices.

For society, the solution supports decision making processes that favor food security, preservation of biomes, and the strengthening of Brazil's competitiveness in global markets.

Technologies of this nature enhance and strengthen tropical sustainability indicators, which are strategic for consolidating Brazil's position by characterizing the unique details of national production systems in the face of sustainability requirements such as the EUDR, thus reinforcing its leadership in resilient agriculture adapted to the impacts of climate change.

How this solution contributes to national competitiveness

This solution strengthens the competitiveness of Brazilian agribusiness by integrating productivity, sustainability, and added value, in line with global demands for resilient agricultural systems with low environmental impact:

- Diversification and production efficiency: ICLF models permit simultaneous production

of grains, meat, and wood in the same area, optimizing land use and reducing operating costs. This increases profitability per hectare, making Brazilian products (like soybeans, beef, and eucalyptus) more competitive on the national and international markets.

- Access to demanding markets: the ability to quantify carbon stocks and improve soil quality, as demonstrated by this technology, complies with regulations such as the EUDR and low emission certifications (for instance, Low-Carbon Meat). This adds value to Brazilian exports, especially to countries that prioritize sustainability.
- Attracting green investments: the completeness of the data on emissions and removals, in line with the 2006 IPCC guidelines, increases Brazil's credibility in reports such as the BTR, attracting climate finance and partnerships with international institutions interested in sustainable agricultural systems.

How this solution reduces exposure to risk and increases adaptive capacity

The solution reduces climate and economic vulnerabilities by promoting more resilient and diversified production systems, strengthening the adaptive capacity of the agricultural sector:

- Reducing climate risks: ICLF systems supported by this technology improve soil fertility and increase carbon stocks, making areas less susceptible to extreme events such as drought or erosion. The presence of trees (in silvopastoral systems) and crop rotation (in agropastoral systems) also regulate the microclimate and humidity, protecting production.
- Mitigating economic risks: diversifying production (of grains, meat, and wood) reduces dependence on a single source of income, cushioning the impact of market

fluctuations or crop failures. This is especially valuable in regions like the Cerrado, where monoculture can be more vulnerable.

- Adaptive capacity: physical models make it possible to test different spatial and temporal arrangements, adapting systems to local conditions and climate projections (such as temperature increases or changes in rainfall patterns). This flexibility ensures continuity of production in adverse scenarios.

How can society perceive and understand the strategic importance of the development of this solution

Effectively communicating the benefits of this solution can highlight its role in food safety, environmental preservation, and innovation, gaining support from Brazilian and global society:

- Connection with food security and the environment: for urban audiences, technology can be presented as a way of producing more food (grains and meat) while preserving the soil and climate, ensuring the supply of essential products and the health of ecosystems that directly influence quality of life (like water and air).
- Practical value for producers: for farmers, the solution can be demonstrated as a strategy that increases profitability and protects land from degradation, with concrete examples (such as model farms using ICLF systems) showcased at fairs or rural extension programs.
- Sustainable leadership narrative: society can perceive this technology as a milestone in Brazil's pioneering efforts to integrate agriculture, livestock, and forestry, showing how the country is tackling climate change with practical solutions. This potential can be exploited in educational campaigns or international events such as the COP, reinforcing the strategic relevance of tropical agricultural science.

Impact on the sustainability of food production in Brazil and worldwide

This solution has a direct impact on the sustainability of agricultural production in Brazil, with positive externalities that position the country as a global leader in integrated and resilient systems.

Direct impacts in Brazil

Sustainable productivity: improving soil quality and increasing carbon stocks in ICLF systems guarantees long-term production of grains, meat, and timber, reducing the need to clear new areas and preserving biomes such as the Cerrado and the Amazon.

Food security: the diversification and resilience of these systems ensure a continuous supply of basic foodstuffs (such as corn, soy, and meat), meeting domestic demand and exports, which account for a significant portion of the Brazilian economy.

Emissions reduction: by capturing carbon in the soil and biomass (trees in ICLF systems), the solution mitigates GHG emissions from the agricultural sector, in line with the goals of the ABC Plan and national climate commitments, such as the NDC.

Global externalities

Replicable model: the physical models of ICLF can be adapted by other tropical countries (such as Colombia and Nigeria), offering a sustainable alternative to monoculture and deforestation, with positive impacts on global emissions reductions and food security.

Contribution to the global climate: carbon sequestration in Brazilian soils benefits the entire planet by mitigating global warming, while diversified production contributes to stabilizing food supplies on international markets.

Solution 5 – Netflora

The Netflora technology (Figure 7.3), aimed at semi-automated forest inventories and monitoring of management systems in the Amazon, offers practical benefits to society by promoting the sustainable management of forest resources and improving the transparency of the national emissions inventory.

By generating accurate data on carbon stocks, emissions, and land use, Netflora facilitates certification of forest products like timber and nuts according to international standards, supporting the local economy and food security of Amazonian communities. This detailed data contributes to a more accurate understanding of tropical agricultural systems, especially where forests and agriculture meet, by quantifying GHG removals and emissions in the LULUCF sector in line with Tier 2 of the IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement,



Figure 7.3. Netflora, a methodology developed by Embrapa, brings together a set of algorithms trained with artificial intelligence (AI) to recognize forest species. Based on botanical characteristics available in a database, this learning process makes it possible to identify commercially valuable trees and pinpoint their exact location in the forest.

Netflora can be a strategic tool to lend robustness to the extrapolations associated with use of forest resources, which can help international reviewers understand the impact of sustainable forest management on carbon sequestration in the national NDC.

For society, this technology preserves the Amazon, reduces pressure on agricultural land, and strengthens Brazil's credibility in global markets, contributing to international understanding of tropical sustainability indicators and thus reducing regulatory pressures such as those defined by the EUDR.

This is one of several technologies that support the consolidation of Brazil's leadership in tropical bioeconomy and global climate action.

How this solution contributes to national competitiveness

Netflora strengthens Brazil's competitiveness by improving sustainable forest management and environmental traceability, meeting global demands for responsibly sourced tropical products:

- **Valuing forest products:** by enabling accurate and consistent forest inventories, Netflora facilitates the certification of timber and non-timber forest products (like Brazil nuts and açai) via international standards such as those of the Forest Stewardship Council (FSC). This certification increases the market value of these products and widens access to demanding markets, such as those in Europe and the United States.
- **Credibility in climate reports:** the consistency of the data generated by Netflora, in accordance with the 2006 IPCC guidelines, reinforces Brazil's reliability in reports such as the BTR, an essential element for international negotiations and for preventing trade barriers related to deforestation.

- Attracting investment: the ability to spatialize emissions and monitor carbon stocks in forest management systems attracts climate finance (for instance, Reducing Emissions from Deforestation and Forest Degradation, REDD+) and partnerships with global organizations interested in conservation and sustainable agriculture, consolidating Brazil's position as a leader in the tropical bioeconomy.

How this solution reduces exposure to risk and increases adaptive capacity

Netflora reduces vulnerabilities associated with logging and climate change, promoting more resilient management of natural resources in the Amazon:

- Reducing regulatory and environmental risks: accurate monitoring of land use and emissions prevents illegal or unsustainable practices, reducing the risk of international sanctions and fines for deforestation. This protects the Brazilian forest-based economy from losses associated with market restrictions or reputation.
- Preventing forest degradation: by planning and executing inventories in a semi-automated manner, Netflora optimizes forest management, avoiding over-exploitation that compromises natural regeneration and increases vulnerability to fires or loss of biodiversity, common risks in tropical systems.
- Adaptive capacity: spatialization of emissions and carbon stocks allows for adjustments in forest management based on up-to-date data (such as climate changes that affect tree growth or soil moisture), ensuring the long-term sustainability of production and supporting adaptation to climate variations in the Amazon.

How can society perceive and understand the strategic importance of the development of this solution

Communicating the benefits of Netflora can highlight its role in the conservation of the Amazon, in the local economy, and in Brazil's environmental leadership, gaining support from society in the country as well as abroad:

- Preserving the Amazon: for the urban public, Netflora can be presented as a tool that protects the Amazon (which is essential for the climate and biodiversity) while permitting the sustainable use of its resources, connecting this protection to issues such as air quality and rainfall that affect the whole country.
- Benefit for local communities: for rural and indigenous populations in the Amazon, Netflora can be understood as direct support for the forest economy (for instance, managed timber and products from social and biodiversity products), promoting livelihoods without destroying the forest, with practical examples in training or cooperatives.
- Image of innovation and responsibility: society can see Netflora as a symbol of Brazil's commitment to science and sustainability, showing how the country is leading the way in the management of tropical forests amid a global context of climate crisis. This can be emphasized in educational campaigns or events such as the COP, strengthening national pride.

Impact on the sustainability of food production in Brazil and worldwide

Although Netflora is focused on forestry systems, its indirect effects contribute to the sustainability of food production in Brazil and generate positive externalities on a global scale, especially in tropical regions.

Direct impacts in Brazil

Sustainability of the bioeconomy: precision forest management, supported by Netflora, ensures a sustainable supply of forest products that complement food production (like Brazil nuts and vegetable oils), which in turn is essential for food security and the economy of Amazonian communities.

Reducing pressure on agricultural land: by promoting sustainable use of forests, Netflora reduces the need to convert forest areas into pastures or crops, preserving soils and ecosystems that provide fundamental ecosystem services to agriculture (such as pollination and water regulation).

Climate mitigation: spatializing emissions and increasing carbon stocks in managed areas contributes to the goals of the ABC+ Plan and the Brazilian NDC, reducing the climate impact of the LULUCF sector, which affects agricultural production.

Global externalities

Model for tropical forests: Netflora can be adapted by other countries with tropical forests (Indonesia, Congo), offering a consistent methodology for forest inventories and sustainable management with a direct impact on global emissions reductions and biodiversity conservation.

Contribution to climate and global agriculture: the preservation of the Amazon, facilitated by Netflora, benefits the world by maintaining one of the largest carbon sinks on the planet and regulating climate patterns that affect food production in other regions (like rainfall in South America and Africa, for example).

Independent leadership: the investment in Netflora reflects Brazil's commitment to tropical sustainability, regardless of the policies of other countries. This initiative positions the country as a leader in forest management technologies,

influencing global standards and climate negotiations, such as the UNFCCC.

Solution 6 – Soil Bioanalysis technology

The Bionanálise de Solo (Soil Bioanalysis, BioAS) technology, which integrates biological analyses (enzymes) and chemical assays to assess soil health, offers practical benefits for society by optimizing agricultural management and improving the transparency of the national emissions inventory (Figure 7.4).

By providing detailed data on fertility, nutrient cycling, and carbon stocks in tropical soils, BioAS permits precise adjustments in fertilizer application, reducing costs and boosting the productivity of crops such as soybeans, corn, and sugarcane, which are essential for food security.

These data contribute to a more accurate understanding of tropical agricultural systems, allowing robust estimates of GHG emissions and removals in the agricultural sector, and will certainly contribute to future advances in the inventory towards the incorporation of tropical methods compatible with Tier 3 of the IPCC guidelines.



Photo: Fabiano Bastos

Figure 7.4. Embrapa's BioAS technology adds a biological component to routine soil analysis, and is based on the analysis of the activity of the enzymes arylsulphatase and beta-glucosidase, which are associated with the sulfur and carbon cycles, respectively.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, BioAS is an example of a technical-scientific advance that strengthens domestic data, including emission factors and activity data. These inputs can contribute to extrapolations and assessments of the quality of the information available to decision-makers. The availability of this type of data and tool represents a relevant support for developing policies that promote reduction of national emissions, by quantifying carbon sequestration in healthier soils and reductions in the use of inputs.

For society, this technology promotes sustainability, protects against soil degradation, and strengthens Brazil's competitiveness in global markets, broadening understanding of the biological processes that occur in tropical agricultural soils and consequently reducing international pressure for the unilateral definition of sustainability indicators, as is the case with the EUDR requirements.

Meanwhile, BioAS, as part of a repertoire of technologies developed by national agricultural science, reinforces the country's leadership in resilient tropical agriculture adapted to the negative impacts of climate change.

How this solution contributes to national competitiveness

BioAS strengthens the competitiveness of Brazilian agribusiness by offering a detailed and accurate analysis of soil health, optimizing production and aligning with global demands for sustainable agricultural practices.

- Increased agricultural efficiency: by integrating biological (enzymes) and chemical parameters, BioAS allows more precise soil management, adjusting the application of fertilizers and other inputs to the real needs of the crops. This reduces costs and increases productivity per hectare, making Brazilian

tropical products (like soy, corn, and coffee) more competitive on the global market.

- Certification and traceability: precision in assessing soil quality and carbon stocks (a by-product of sustainable management) facilitates certification of practices with a low environmental impact, meeting the requirements of international markets like the European Union, which value sustainability in product origins.
- Technological differential: BioAS positions Brazil as a leader in tropical soil analysis technologies, a competitive differential in international negotiations and partnerships with countries seeking solutions for degraded or highly complex soils typical of tropical regions.

How this solution reduces exposure to risk and increases adaptive capacity

BioAS reduces vulnerabilities related to soil degradation and climate change, promoting more resilient and adaptable agricultural systems.

- Reducing the risk of degradation: a precise assessment of soil health (via enzymes and the soil quality index [IQS]) identifies areas at risk of loss of fertility or erosion, making it possible to implement preventive interventions such as crop rotation or addition of organic matter. This is crucial in tropical soils, which are naturally nutrient-poor and susceptible to deterioration.
- Mitigating climate risks: healthier soils, with a greater capacity for cycling and storing nutrients, are more resilient to extreme events (like prolonged droughts or intense rains), which are common in tropical regions such as the Cerrado. BioAS helps maintain productivity even under climatic stress.
- Adaptive capacity: by providing detailed soil data, BioAS allows adjustments to agricultural

management based on local conditions and climate projections (such as increased temperature or reduced humidity), adapting production to long-term changes and ensuring sustainability in adverse scenarios.

How can society perceive and understand the strategic importance of the development of this solution

Communicating the benefits of BioAS can highlight its role in agricultural productivity, environmental conservation and innovation, strengthening support from Brazilian and international society.

- Connection with food and the environment: for the urban public, BioAS can be presented as a technology that ensures food production by taking care of the “foundation” of agriculture (the soil) while protecting the environment. This approach connects it to issues such as food security, water quality, and biodiversity protection.
- Practical value for farmers: for farmers, BioAS can be promoted as a tool that increases productivity and reduces fertilizer costs, with concrete examples presented at field days or through cooperatives (for instance: “more soy with fewer inputs”).
- Symbol of scientific leadership: society can understand BioAS as proof of Brazil’s pioneering spirit in sustainable tropical agriculture, demonstrating how the country uses advanced science to tackle global challenges such as soil degradation and climate change. This can be emphasized in educational campaigns or international events.

Impact on the sustainability of food production in Brazil and worldwide

BioAS has a direct impact on the sustainability of agricultural production in Brazil, with positive externalities that reinforce the country’s leadership in resilient, low-carbon tropical practices.

Direct impacts in Brazil

Long-term productivity: improving soil health, as assessed by BioAS, guarantees fertility and productive capacity over time, an essential aspect for tropical crops such as soybeans, corn, and sugarcane, which underpin the national economy and food security.

Carbon removal: healthier soils with greater biological activity (enzymes) and storage capacity sequester more carbon, reducing net emissions from the agricultural sector and aligning with the goals of the ABC Plan and the Brazilian NDC.

Reducing inputs: more precise management reduces dependence on chemical fertilizers, reducing costs and environmental impacts (like nitrogen leaching, for example) while contributing to the preservation of tropical ecosystems such as the Cerrado and the Amazon.

Global externalities

Replicable model: BioAS can be adapted by other tropical countries (like Thailand and Kenya) that face similar challenges with fragile soils, offering an innovative approach to sustainable management and strengthening global food resilience.

Contribution to the global climate: the increase in carbon stocks in Brazilian agricultural soils benefits the planet by mitigating global warming, while efficient production of tropical food stabilizes supply in a scenario where climate crises affect other regions.

Independent leadership: the investment in BioAS reflects Brazil’s commitment to sustainability, regardless of the policies of other countries. This positions the country as a leader in precision technologies for tropical soils, influencing global standards and climate negotiations, such as the UNFCCC.

Solution 7 – Life cycle inventories for agricultural products

Life cycle inventories (LCI) for agricultural products offer practical benefits to society by quantifying the environmental impacts of products such as corn, soy, milk, and meat, promoting sustainability and improving database interoperability. These databases can feed into the national information system and consequently support the transparency of the national emissions inventory.

By assessing GHG emissions in detail from production to the final destination, LCI identify critical points and opportunities for efficiency, allowing producers to optimize the use of resources, reduce costs, and minimize environmental impacts. This robust data contributes to a more accurate understanding of tropical agricultural systems, providing detailed estimates of emissions and removals in the agricultural sector. Interoperability of databases and the coordinated design of experiments and analyses enhance the national analytical effort, and could represent an important area for improvement and cooperation.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, the existence of corporate protocols (like Embrapa's Integra Carbono platform) could unify efforts to reduce GHG emissions in Brazil, and bring the data acquisition strategies carried out within the context of the LCI closer to the inventory and transparency efforts observed in the BTR.

For society, the technology guarantees availability of food choices with a smaller environmental footprint, strengthens development of tropical sustainability indicators, and increases Brazil's competitiveness in global markets. It also broadens the debate on sustainability, highlighting the strategic nature of tropical agricultural production systems, in line with market instruments such as the EUDR.

The development of LCI reinforces leadership in sustainable tropical agriculture based on robust

data and scientific evidence, supporting public policies, and offering society robust traceability tools, an increasingly pressing demand from conscious consumers.

How this solution contributes to national competitiveness

Conducting LCI for agricultural products strengthens the competitiveness of Brazilian agribusiness by offering detailed, accurate, and traceable data, in line with global demands for transparency in proving sustainable agricultural production.

How this solution reduces exposure to risk and increases adaptive capacity

The construction of LCI makes it possible to quantify GHG emissions from production systems, identifying critical points and opportunities to increase efficiency and mitigate emissions.

- Risk reduction: by assessing the environmental impacts of a product, from production to end destination, critical areas can be identified, such as excessive use of resources or GHG emissions. This in turn makes it possible to improve resource efficiency, reduce costs, and mitigate environmental impacts.
- Adaptive capacity: the LCI is a guideline for adopting more sustainable agricultural practices, based on increasing efficiency and increasing resilience to climate change.

It also anticipates regulatory and market risks, helping to meet demands for more sustainable products and promoting more efficient and competitive production.

How can society perceive and understand the strategic importance of the development of this solution

This solution helps provide concrete data on the environmental impact of agricultural products,

making it possible to take actions toward mitigation in order to more efficiently manage natural resources in different processes and phases of the life cycle (in the case of milk, for example). It can also guide public policies aimed at sustainability and reducing environmental and economic risks in the sector.

- Connection with food and the environment: LCI are tools for understanding the environmental impacts of agricultural production and guiding the implementation of practices and technologies to mitigate GHG emissions and increase production efficiency, guaranteeing food availability.
- Practical value for farmers: for producers, this solution offers detailed information on reference production systems, which indicate points for improving efficiency and reducing costs, such as increasing circularity in the use of inputs and disposal of waste generated.
- Symbol of scientific leadership: LCI are globally recognized for following international norms and guidelines for standardizing methodology. Brazil has inventories of the main agricultural commodities (corn, soybeans, sugarcane, coffee), which represent typical production systems characterized by producing regions, as well as inventories of livestock products such as milk and meat.

Impact on the sustainability of food production in Brazil and worldwide

Direct impacts in Brazil

LCI make it possible to quantify emissions throughout the life cycle and guide mitigation strategies in order to optimize the use of resources, which reduces costs and decreases pressure on the environment, such as risks associated with a shortage or increased GHG emissions. They also provide support for complying with stricter environmental regulations and market demands for products with a lower environmental impact.

Global externalities

LCI provide identity for Brazilian products and transparency to information about environmental impacts and sustainable practices applied to production systems, promoting competitiveness in the market.

The construction of LCI for agricultural products highlights Brazil for generating accurate information that demonstrates environmental performance in production. This solution provides strategic information for the effective implementation of sustainable development in the practices of the Brazilian agricultural sector, and offers data to support thousands of studies that consider the life cycle perspective of products associated with national and international agribusiness.

Solution 8 – RumenGases

The RumenGases technology, developed at Embrapa Dairy Cattle's Multiusuário de Bioeficiência e Sustentabilidade da Pecuária (Multiuser Livestock Bioefficiency and Sustainability Laboratory, LMBS), offers practical benefits to society by quantifying and mitigating enteric methane emissions in ruminants, promoting sustainability and making the national emissions inventory more transparent. Using state-of-the-art methods like respirometry chambers and tracer gas techniques, RumenGases generates accurate data on emissions in tropical livestock systems, permitting assessment of feeding strategies and natural additives that reduce methane and also simulating climatic stress conditions to increase production efficiency.

These data help advance diagnosis and mitigation strategies for enteric methane in ruminants in Brazil, permitting a more accurate understanding of tropical agricultural systems and providing detailed estimates of GHG emissions in the livestock sector, in line with Tier 2 of the IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, RumenGases is an example of national investment in cutting-edge scientific improvement that strengthens generation of strategic data to support the decision making process. The analytical and instrumental capacity offered by RumenGases positions the country as a competitive leader in tropical livestock systems and makes it a strategic tool for supporting adjustments in the national emissions reduction trajectory by demonstrating the impact of sustainable practices, such as optimized diets and adapted management.

For society, this technology guarantees production of nutritious foods like milk and meat with less environmental impact; strengthens Brazil's competitiveness; broadens understanding of the attributes of tropical production systems in global markets; and reinforces leadership in sustainable livestock farming, supporting food security and climate mitigation.

How this solution contributes to national competitiveness

The LMBS, constructed in the experimental field at Embrapa Dairy Cattle, represents one of the sectors with the most important research structures for evaluating enteric methane, including the gold standard methodology of respirometry chambers, the sulfur hexafluoride (SF₆) tracer gas technique, along with in vitro assays and spot sampling using face masks. It is a world reference among laboratories studying this gas. The research it conducts made it possible to standardize methods and create a national database on methane emissions in ruminants in tropical climates.

How this solution reduces exposure to risk and increases adaptive capacity

The LMBS includes four main areas of ruminant research: metabolism and environmental

impacts of livestock farming; biotechnology and environmental management; precision livestock farming; and animal health. With lines of research in each of these areas, this laboratory has high-tech equipment for carrying out analyses.

- Risk reduction: research into assessment and mitigation of GHG emissions, aligned with nutritional requirements and feed efficiency, aims to establish strategies for improving the efficiency of livestock production systems and reducing GHG emissions. These studies have also made it possible to evaluate over 300 natural compounds with potential as enteric methane mitigating feed additives, as well as various feeding strategies intended to reduce emissions of this gas.
- Adaptive capacity: the lab has the research capacity to simulate stress conditions in production systems, anticipating and seeking solutions to adapt these systems to climate challenges. The lines of action include targeting genetic improvement, reproductive efficiency, animal health and welfare, as well as production efficiency.

The facility also has a climate chamber for adult cattle, which permits studies on heat stress to evaluate the effect of stressful conditions on animal performance and test strategies to reduce resulting impacts. This helps reduce the intensity of GHG emissions per unit of product generated (milk or meat).

How can society perceive and understand the strategic importance of the development of this solution

The solution has a national reach, is open in nature, takes an interdisciplinary approach, and is capable of creating and providing integrated solutions for scientific and technological projects. It is one of the few laboratories in the world with respirometry chambers currently in operation, which permits research using the

most accurate methodology for estimating the energy requirements for ruminants reared in tropical conditions, as well as methane emissions in different management strategies for both large and small ruminants.

- Connection with food and the environment: the solution plays a fundamental role in analyzing the environmental impacts of food production on a global scale. Livestock farming, although responsible for a portion of GHG emissions, is also vital to produce food with high nutritional value. By quantifying these emissions, research provides essential data to understand how food systems contribute to climate change and permits the development of more effective and sustainable mitigation strategies. In this way, the integration between climate science and food security becomes crucial in promoting agricultural practices that reduce environmental impacts without compromising the production and supply of food to the population.
- Practical value for farmers: this solution offers producers access to information and strategies that increase the efficiency of milk production in typically Brazilian systems while taking into account the country's characteristic breeds, diets, and climate. It also encourages the adoption of technologies adapted to local conditions to mitigate GHG emissions.

Impact on the sustainability of food production in Brazil and worldwide

Direct impacts in Brazil

This solution provides a foundation to move forward with the construction of national livestock emission inventories for Tier 3. The laboratory structure has the capacity to generate continuous information on GHG emissions, resulting in more refined and specific data for Brazil's estimates. This contributes to the definition of assertive mitigation strategies, based on

information adapted to the characteristics of the Brazilian climate, herd, and production systems.

Global externalities

The recognition of advanced research into livestock emissions, mitigation, and adaptation has fostered international partnerships.

This solution is intended to position Brazil at the forefront of efficient animal production, accurate data generation, and emissions mitigation.

The RumenGases project carried out by Embrapa Dairy Cattle from 2011 to 2016 was intended to advance the diagnosis and mitigation strategies of enteric CH₄ in ruminants in Brazil. This project made it possible to establish the Multiuser Bioefficiency Complex, a reference in assessment of enteric CH₄ specializing in methodologies such as respirometry chambers, SF₆ tracer gas, in vitro techniques and spot sampling using face masks (Figure 7.5).

This has made it possible to standardize methods and create a national database on CH₄ emissions in ruminants. The laboratory's ability to generate information on an ongoing basis is a solid basis for building national livestock inventories at the Tier 3 level.

The cost of implementing LCI is a challenge, especially for small tropical producers. In Brazil, agri-food companies are investing in the expansion of data collection to construct LCI.



Photo: Márcio Brigatto

Figure 7.5. Multiuser Livestock Bioefficiency and Sustainability Laboratory (LMBS) at Embrapa Dairy Cattle in Coronel Pacheco, Minas Gerais.

Embrapa, in partnership with Instituto Brasileiro de Informação em Ciência e Tecnologia (the Brazilian Institute of Information on Science and Technology), has been developing and providing LCI for agricultural products for free public access, in an internationally recognized format.

Solution 9 – New indicators for changes in carbon stocks in forest soils

This technology offers practical benefits to society by providing accurate national data on carbon stocks in the soils of planted forests, promoting sustainability and improving the transparency of the national emissions inventory.

By developing national indices of alteration in carbon (IAC) for forest plantations and for pasture to eucalyptus conversions, this technology reveals that Brazilian forestry systems sequester more carbon than previously estimated, diminishing the perception of soil losses. This detailed data contributes to a more accurate understanding of tropical agricultural systems, especially where forests and agriculture meet, by quantifying GHG removals and emissions in the LULUCF sector, in line with Tier 2 of the IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, the national effort to adequately characterize processes of change in land use and forests by developing national indices reinforces the robustness of the national decision making process. This initiative supports demonstration of the positive impact of reforestation on carbon sequestration as a strategic action, which should be expanded and supported over the coming years.

For society, the solution strengthens the competitiveness of forest products in global markets, meets requirements such as the EUDR, reduces deforestation pressure, and supports public policies such as the ABC+ Plan,

consolidating Brazil's leadership in sustainable forest production and climate mitigation.

How this solution contributes to national competitiveness

In order to estimate the carbon stocks of the reforestation sector, Brazil currently adopts an index of alterations in soil carbon stocks (IAC) of 0.673, originally indicated for agricultural crops in international studies. This factor penalizes forest plantations, suggesting that more than 30% of the carbon stored in the soil is lost through conversion for land use. A national dataset was analyzed, covering nine states (RS, SC, PR, SP, ES, MG, BA, PA and MS), with a total area of planted forests currently amounting to over 8.6 million hectares. Based on this data, the IAC for conversion of use to forest plantations is 0.95; in specific conversions, such as pasture to eucalyptus, there is an 11% gain in soil carbon stock (IAC=1.11). The new index was applied in the fourth national inventory. Adopting values that reflect the national reality in terms of carbon sequestration is essential for the reliability of official national data on GHG emissions and removals, and also serves as a foundation to guide drafting and implementation of public policies to control and mitigate climate change, adding continuous improvements to the tools used to manage these policies. Amid growing demands from consumer markets regarding environmental policies and commitments, this new information is crucial to construct quantitative emissions scenarios for commercial transactions and guarantee national competitiveness.

How this solution reduces exposure to risk and increases adaptive capacity

The representation of the national reality, in terms of the production system and GHG emissions, is essential to guide public policies and effective actions to control climate change,

in terms of both mitigation and climate adaptation. The parameters that prove the use of this information in favor of adaptive capacity and reducing agricultural risk involve, among other aspects, encouraging expansion of the area of these more resilient production systems, based on their capacity for climate mitigation and adaptation as advocated by the ABC+ Plan. This helps reduce pressure to clear new areas and exploit native species and, in turn, deforestation. These parameters also mitigate financial risks by helping to meet the requirements for reporting GHG emissions related to export products, which guarantees accessibility and competitiveness in international markets and also permits emissions offsets and incentives for continued production. These benefits are important for both small producers and large forest-based enterprises.

How can society perceive and understand the strategic importance of the development of this solution

An increasing number of organizations are paying attention to global pacts related to climate change and sustainable development, seeking new production standards that minimize environmental impacts and boost the environmental efficiency of processes. It is becoming increasingly important for organizations to communicate their sustainability actions as a result of more demanding consumers, the need for transparency, and social and environmental responsibility. In the face of growing international demand for more transparent and up-to-date sustainability metrics (especially for export products and in terms of new carbon tax mechanisms), these more accurate and representative indicators are being appropriated by the production sector through tools and other mechanisms that incorporate the new information. Generating these new indicators is part of Embrapa's activities to ensure the scientific and technical backing that is

essential for their acceptance in the face of legal and regulatory process requirements.

Impact on the sustainability of food production in Brazil and worldwide

This section highlights direct impacts and externalities in other countries and globally. Brazil leads the way and invests in sustainability, regardless of the visions or directions adopted by other countries.

This solution strives to bring transparency and representativeness to the construction of inventories that faithfully depict the national reality, while also advancing methodologically towards the most detailed level of information (Tier 3). It also contributes to defining targeted and assertive strategies for mitigating GHG emissions, based on information generated in Brazil's territory, which reflects national technologies and soil and climate conditions. Specifically in terms of global externalities, the new indicators provide support to defend sustainable production in the country, with income generation, social justice, and care for the environment. In this way, together with other information, these indicators have the potential to position Brazil at the forefront of high-tech forest-based production and climate change control by generating accurate data and encouraging mitigation of GHG emissions.

Solution 10 – Carbon Matte

The Carbon Matte technology establishes a database system that records, organizes, and calculates carbon stocks and GHG emissions in yerba mate (*Ilex paraguariensis*) production systems, offering practical benefits to society by promoting sustainable management and improving the transparency of the national emissions inventory.

The solution supports the quantification of CO₂, CH₄, and N₂O emissions, along with assessment of carbon stocks in yerba mate plantations,

allowing producers and companies to identify critical points, optimize the use of inputs and reduce environmental impacts, and guarantee productivity and added value for products derived from yerba mate.

This detailed data contributes to a more accurate understanding of tropical agricultural systems, especially agroforestry systems, by providing robust estimates of removals and emissions in the LULUCF sector of this socially relevant native species, in line with Tier 2 of the IPCC guidelines.

During the technical analysis of the BTR, as defined by the MPGs of the Paris Agreement, the database generated by Carbon Matte supports the development of emission factors and domestic activity data, which in turn strengthens emissions estimates and supports the decision making process needed to justify the national emissions reduction trajectory. The technology supports national efforts to characterize the sustainability of tropical production systems and help reduce emissions by demonstrating the mitigating potential of yerba mate and supporting policies such as the ABC+ Plan.

For society, this technology strengthens competitiveness in global markets, demonstrating the specific qualities of tropical production systems in the face of sustainability requirements like EUDR, and reinforces Brazil's leadership in the tropical bioeconomy, promoting sustainability and valuing biodiversity.

How this solution contributes to national competitiveness

Carbon Matte is an electronic spreadsheet for recording, organizing, calculating (with an automated routine), and analyzing data from yerba mate production systems, with applications for estimating carbon stocks and GHG flows.

The tool was developed in a comprehensive manner that includes all the compartments that store carbon, as well as the emission

sources of the main GHGs (carbon dioxide [CO₂], methane [CH₄], and nitrous oxide [N₂O]). Yerba mate is a native species of economic and social importance. Environmentally, it represents an option for sustainable forestry in permanent preservation and legal reserve areas, with high potential for generating ecosystem services such as carbon storage. The national climate change policy and the ABC+ Plan itself have listed the cultivation of yerba mate as a potential mitigator, which gives rise to a greater understanding of the relationship between the production of yerba mate and the mitigation of GHG emissions. This perspective justifies the need for a specific calculation tool.

From this perspective, the tool is intended for use by professionals in the field of environmental impact assessment, rural producers who want to manage their carbon removals and emissions, as well as companies and certifiers looking to measure their assets, account carbon emissions and stocks, or participate in corporate campaigns to meet the Sustainable Development Goals. Opening up new markets involves managing not only production, but also how the product is produced.

How this solution reduces exposure to risk and increases adaptive capacity

Carbon Matte quantifies GHG emissions from yerba mate production systems, diagnosing critical points and identifying opportunities to improve production efficiency and mitigate emissions. In terms of risk, an accurate diagnosis of the production cycle makes it possible to identify which inputs are responsible for most of the emissions, in order to identify less impactful alternatives that guarantee productivity. This in turn permits more efficient use of resources, reduced production costs, and mitigation of environmental impacts. In terms of adaptive capacity, Carbon Matte is a guideline for more sustainable farming practices, which promote

both the efficiency and resilience of production systems in the face of climate change. It also supports and anticipates the management of regulatory and market risks, helping to meet the demands that ensure competitiveness in the forest-based sector.

How can society perceive and understand the strategic importance of the development of this solution

This tool is available for use by the productive sector, and has already served as a reference for large companies that process raw yerba mate, ensuring environmental transparency in production and indicating aspects that require intervention to improve performance in the production system. The tool is being incorporated by farmers through technical assistance and non-governmental organizations (NGOs) working in the sector. The benefits of using it to generate sustainability parameters for yerba mate plantations include the ability to construct scenarios to assess different practices and techniques used in cultivation, considering the sensitivity of the interventions in terms of carbon removal and GHG emissions. Use of this tool is not only a mechanism to support climate management on the property, but can also support adding value to products derived from yerba mate, culminating in greater financial returns for producers.

Impact on the sustainability of food production in Brazil and worldwide

The yerba mate sector is at a unique moment, considering appreciation for this species domestically, the discovery of new nutraceutical properties, and development of new products, factors that have led to an increase in global demand that is expanding the consumer market and even driving requests for designation of origin. This scenario is undoubtedly catalyzing new opportunities for recognition of environmental

benefits, especially in the fight against climate change. Carbon Matte objectively reflects this possibility by quantifying carbon stocks and GHG emissions, positioning Brazil as an active player in valuing its biodiversity and generating accurate information that demonstrates the environmental performance of production of yerba mate.

Future prospects

Advancing to Tier 3 – Opportunities and challenges in tropical systems

Brazil's transition to Tier 3 methods for estimating GHG emissions in the agricultural sector is a strategic step towards consolidating a monitoring and inventory plan and infrastructure in the medium and long term, especially in the new context of the Paris Agreement and the BTRs. According to the 2006 IPCC guidelines, Tier 3 uses specific models and high-resolution local data, offering greater precision compared to the Tier 1 (standard factors) and Tier 2 (national factors) methods. In tropical systems characterized by high climatic and biological variability, this approach is essential to capture the dynamics of processes such as enteric fermentation in cattle and emissions of nitrous oxide (N₂O) from managed soils, which are often underestimated by current methods.

One of the main opportunities of Tier 3 lies in the ability to reflect the specific characteristics of the tropics, such as the rapid carbon cycle in soils in hot and humid climate regions, and the complex interactions in integrated systems such as ICLF. The 2024 BTR already signals advances in the use of Tier 2 for livestock, but adoption of calibrated regional models, such as Century or DNDC (DeNitrification-DeComposition) adapted to Brazil, could reduce uncertainties by 20 to 70%, approaching the levels observed in developed countries (10–15%). This progress will strengthen the credibility of the national inventory and its alignment with the NDC targets, and potentially

increase acceptance of Brazilian agricultural products in international trade.

Tropical systems, however, pose significant challenges to the implementation of Tier 3. The diversity of biomes (such as the Amazon, Cerrado, Caatinga, and Pampa) and heterogeneity of agricultural practices including irrigated rice cultivation and extensive livestock farming demand a robust infrastructure for collecting primary data. The lack of continuous monitoring networks, such as flow chambers to measure methane (CH₄) or N₂O sensors in the soil, limits the generation of representative data (Assis et al., 2020), an obstacle that the plan will have to overcome with strategic investments.

Another challenge is the high cost associated with developing and validating Tier 3 models. In the tropics, seasonal variability of rainfall and intense microbial activity require frequent and spatially detailed measurements, in contrast to temperate systems where processes are more stable (Davidson; Artaxo, 2004). As highlighted earlier in this chapter, countries like New Zealand have overcome this barrier through public-private partnerships and continuous funding, a model that Brazil could adapt, possibly with GEF support.

The opportunity to position Brazil as a leader in sustainable tropical agriculture is a powerful incentive. Tier 3 would make it possible to precisely quantify the benefits of practices such as ICLF systems, which sequester carbon in tropical soils at higher rates than in cold climate regions (Medeiros et al., 2022). This development would not only support the transparency process required under the Paris Agreement, but would also strengthen the competitiveness of Brazilian products on the international market, where traceability of emissions is increasingly valued.

Technical training represents an additional challenge. The transition to Tier 3 requires professionals trained in advanced modeling and data analysis, a gap in tropical Brazil, where training still focuses on conventional

approaches. The plan should include training programs, taking advantage of the expertise held by Embrapa (which has been contributing to national inventories since 1992) in order to create a workforce that is aligned with the demands of the ETF.

Integrating advanced technologies like remote sensing and sensor networks offers an opportunity to overcome the spatial limitations of the tropics (Bustamante et al., 2016). The BTR already uses tools such as PRODES for the LULUCF sector, but the agricultural sector lacks similar systems. The plan could expand platforms such as MCTI's SIRENE, which are interoperable with Embrapa's initiatives, to consolidate tropical data in real time, reduce uncertainties, and expand coverage.

Finally, the move towards Tier 3 in the tropics faces the challenge of political and financial continuity. The Clean Development Mechanism (CDM) (United Nations, 1998), which lost momentum after 2012 due to economic and political instability, serves as a warning. The plan must establish a resilient institutional framework, with long-term commitments between the government, Embrapa, and the private sector, to ensure that scientific advances translate into sustainable climate and economic benefits.

Using BTR data to comply with the Paris Agreement

The 2024 BTR data submitted to the UNFCCC is a key resource for assessing Brazil's compliance with its commitments under the Paris Agreement, especially in the tropical agricultural sector. The ETF requires detailed biennial reports, and the BTR provides a foundation for monitoring progress on NDC targets, such as reducing emissions and promoting sustainable practices. In the tropics, where agriculture is both a source of GHG and a pillar of the economy, this data can guide public policies and strategic investments (Cabral et al., 2024).

One clear opportunity is the use of BTR to identify gaps in estimates of tropical emissions, such as CH₄ from livestock and N₂O emissions from managed soils, which still depend on Tier 1 in many categories. The report quantifies uncertainties (20–70%) and highlights the need for local data, allowing the plan to prioritize key categories for Tier 3. This would align Brazil with the objective of Article 2 of the UNFCCC (United Nations, 1992), to stabilize GHG concentrations without compromising food production.

The tropical climate, with its high variability, complicates the assessment of progress. The BTR estimates gross emissions from the agricultural sector but underestimates carbon removals in systems like ICLF, due to the lack of adapted models (Carvalho et al., 2020). The plan can use this data as a starting point to develop specific indicators, monitoring sustainable practices that respond to the NDC targets and the demands of the 6th IPCC Report (2021) (AR6) to neutralize net emissions (of CO₂) by 2050.

One significant challenge is the integration of BTR data into national policies, such as the ABC+ Plan. Notably, Brazil's Nationally Appropriate Mitigation Actions (NAMA), presented at COP15 in Copenhagen, included agriculture (thanks to the influence of Embrapa), but the BTR does not yet fully reflect the impacts of these policies. The plan should bridge the gap between science and implementation, using data to calibrate incentives and measure results in dynamic tropical systems.

International transparency offers an opportunity for Brazil to highlight its tropical solutions. The BTR, by detailing sources such as enteric fermentation (with Tier 2 in some regions), can be used to negotiate technical and financial support under the Paris Agreement. The plan should structure submissions to the UNFCCC, drawing on examples like Fiji (4/CP.23), emphasizing the resilience of tropical agriculture and attracting investment for advanced monitoring.

The complexity of tropical systems, such as irrigated rice and extensive livestock farming, represents a challenge for the temporal consistency of BTR data (Cerri et al., 2024). Seasonal rainfall and high temperatures change emissions every year, making comparisons with temperate countries difficult. The plan could invest in refined historical series, integrating data from IBGE and Embrapa to ensure the comparability required by the ETF.

The use of BTR to engage the private sector is another opportunity that has not been widely explored. In the tropics, where agriculture is highly relevant in the economic context, the data can guide market strategies, such as certification of products with a low carbon footprint. The plan should create two-way communication channels, inspired by the CDM, for tropical producers to contribute data and benefit from policies in line with the Paris Agreement.

Finally, the challenge of the national scale requires a pragmatic approach. The BTR covers a country that spans a continent, but tropical systems vary between biomes. The plan should disaggregate the data by region, using the BTR as a basis for local policies that comply with the NDC while maintaining food security — one of the pillars of Article 2 of the UNFCCC (United Nations, 1992) — in an increasingly unstable climate scenario.

Life cycle inventories and carbon footprint in the tropics

LCI form the basis for estimating the carbon footprint of agricultural products, and represent a promising tool for monitoring and inventory plans and infrastructure in the medium and long term. In tropical systems, where products like meat, soy, and rice are in high global demand, LCI make it possible to quantify emissions from cultivation to consumption, meeting the traceability requirements of the international market. The 2024 BTR provides an initial basis,

but the plan should expand it to reflect unique tropical characteristics.

One significant opportunity is the use of LCI to value sustainable products from the tropics. Brazil is one of the few countries that has LCI for its main agricultural products, presented at a regional level. Systems like ICLF, which combine production and carbon sequestration, can be certified based on accurate emissions and removals data. This chapter highlights the transition to a decarbonized economy as a window of competitiveness where the plan can position Brazil as a supplier of food with a low carbon footprint, in line with the goals of the Paris Agreement.

Tropical challenges, such as climate variability and the diversity of production practices, make it difficult to unify national LCI; the inventories for Brazilian agricultural products have been and are being constructed at the state or regional levels. The BTR estimates aggregate emissions, but does not detail life cycle stages, such as transportation or processing of agricultural products. The plan should adopt methodologies based on the IPCC guidelines for calculating emissions from livestock farming, making it possible to generate tropicalized emission factors that capture regional environmental dynamics.

The integration of local data is a highly relevant opportunity. In the tropics, CH₄ emissions from livestock farming and N₂O emissions from fertilizers vary by region, and LCI based on Tier 3 could accurately reflect this. The plan can take advantage of the experience of Embrapa, which has been contributing to national inventories since 1992, to create a tropical database that supports globally recognized certifications and can simultaneously support drafting of the national inventory and the BTR as a whole.

The cost of implementing LCI is a challenge, especially for small tropical producers. Unlike developed countries, where funding is plentiful, Brazil faces budgetary constraints. The plan should seek partnerships with the private sector and

incentives from the ABC+ Plan, reducing financial barriers and promoting large-scale adherence.

Finally, the international demand for transparency offers a strategic opportunity. BTR already serves the ETF, but LCI can go further and respond to regulations such as the European Union's rules on deforestation-free supply chains. The plan should align tropical inventories with these standards, using technologies such as the blockchain to trace products from agricultural systems to the end consumer.

The biological complexity of the tropics, including factors like the rapid decomposition of waste and accelerated growth of crops, represents a challenge for LCI. The BTR underestimates these processes, and the plan should incorporate direct measurement mechanisms like flow sensors to create inventories that reflect the tropical reality, differentiating Brazil from more predictable temperate systems.

Strategies for improving the BTR must be formulated dynamically, in conjunction with planning priorities to be implemented according to the ability to mobilize foreseeable and sufficient financial resources. Partnerships with the productive sector can be strategic to accelerate progress and expand results.

In order to improve the monitoring plan and reflect unique tropical characteristics in the next biannual BTR cycles, the following strategies could be implemented in the medium and long term:

- Develop regional emission factors, using direct measurements of CO₂, CH₄, and N₂O flows in systems such as irrigated rice, extensive livestock farming, and ICLF in order to capture the seasonal variability and intense microbial activity of the tropics, rather than relying on generic IPCC factors.
- Identify information gaps and develop strategies to improve activity data. Strengthen Embrapa's corporate database infrastructure, improving information management,

consolidating indicators and developing tools (APIs) that allow database interoperability and generate reports to support national management and communication.

- Expand continuous monitoring networks, integrating remote sensing (such as Sentinel-2 and LiDAR satellites) with *in situ* sensors in biomes like the Amazon, Cerrado, and Pantanal to map emissions and carbon sequestration with high accuracy, especially in ecotone regions and integrated systems such as ICLF, reducing uncertainties in activity data (currently estimated at 5–15% for livestock and 10–20% for degradation).
- Integrate LCI, standardizing methodologies for products such as meat, soybeans, and rice from cultivation to consumption, in order to meet the traceability requirements of the international market, with validation through case studies in different tropical regions.
- Strengthen technical capacity and international collaboration, investing in training researchers and partnerships with institutions such as Embrapa and global networks (such as FLUXNET) to develop models adapted to tropical dynamics, such as N₂O leaching amplified by heavy rainfall.
- Continuous updates to the BTR with cross-validation, incorporating real-time monitoring data and biennial revisions of LCI to reflect changes in land use, agricultural practices, and climate impacts (El Niño droughts, for instance), ensuring temporal consistency and alignment with the NDC targets. When agreed upon and supported by investments in technology and scientific cooperation, these strategies will allow the BTR to evolve into a robust system that can accurately reflect unique tropical characteristics and promote sustainability in the Brazilian agricultural sector.

Finally, LCI can catalyze a technological revolution in the tropics: by integrating BTR data and advancing to Tier 3, the plan will be able to

develop digital tools that empower producers and strengthen food security, complying with Article 2 of the UNFCCC (United Nations, 1992) and positioning Brazil as a global benchmark in tropical sustainability in the twenty-first century.

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Embrapa's role in the Meknes Declaration

Science diplomacy in action

Climate change is a complex global challenge, and for almost a decade (since COP15 in Copenhagen in 2009) agriculture has been at the center of intense negotiations within the framework of the UN Climate Convention. These discussions sought to align multilateralism (negotiations between countries that usually take place within the framework of the UN) with national policies, promoting advances in food security, sustainability, and climate resilience. However, divergent interests between developed and developing countries made progress slow and even more strategic. While developed countries with high emissions from energy and industry advocated greater responsibility in the agricultural sector for removing greenhouse gases from the atmosphere (an activity referred to in the Convention's jargon as "mitigation"), developing countries prioritized concerns about the real current and future impacts of the effects of climate change, an activity referred to in the Convention's jargon as "adaptation" in order to protect vulnerable production systems, which account for only 10% of global emissions, compared to 70% from fossil fuels.

Within this context, Brazil stood out as a defender of the interests of developing countries, with Embrapa playing a crucial role in scientific diplomacy. Its expertise in tropical agriculture, with innovative scientific solutions and technologies that have helped to reduce the cost of production, increase adaptive capacity to water and heat stresses and drought regimes, reduce dependence on fossil fertilizers, and increase productivity, attracted international attention. Embrapa supported the Brazilian delegation from the very start of the climate negotiations, offering robust analysis on issues such as agriculture and transparency and dialoguing with partners from Latin America, Africa, and Asia.

A turning point came at COP21 in Paris in 2015, during a meeting promoted by the World Bank with African agriculture ministers, in the presence of former UN Secretary General Kofi Annan. Developed countries, through the influence of the World Bank, sought support to prioritize mitigation in agriculture, promising carbon credits. But this was risky: carbon removal in agricultural systems is slow, generating insufficient credits, and extreme weather events could jeopardize mitigation efforts.

It was against this backdrop that the team of Embrapa researchers who were part of the Brazilian delegation made a historic intervention. With scientific underpinnings and the institutional weight of Embrapa, the representatives questioned the viability of the



mitigation proposal, highlighting the risk of neglecting adaptation. The team presented the Brazilian case, which prioritized adaptive strategies to cope with climate impacts such as droughts and floods to ensure food security and sustainability. This intervention generated intense debate, raising questions among African ministers and challenging the dominant narrative.

The impact was significant. The intervention paved the way for the Meknes Declaration on Financing Adaptation in African Agriculture (also known as the AAA Initiative), which was drafted in preparation for COP22 in Marrakesh in 2016. This document marked a turning point, emphasizing adaptation as a priority for agriculture in vulnerable countries. The movement culminated at COP23 in 2017, which was presided over by Fiji and saw the adoption of the Koronivia Joint Work on Agriculture, a historic agreement that consolidated adaptation in agricultural systems as the focus of global climate negotiations.

At the end of the meeting in Paris, Kofi Annan personally congratulated the Brazilian team, recognizing the impact of their intervention. With a combination of scientific rigor, charisma, and the backing of Embrapa, Brazilian science diplomacy resolved an impasse that had dragged on for years. The Meknes Declaration and the Koronivia agreement reinforced the importance of adaptation, benefiting developing countries and aligning agriculture with global sustainability goals. This narrative shows how science, combined with strategic diplomacy, can transform international negotiations, promoting a more resilient future for global agriculture.

Agriculture plays a central role in facing climate challenges: it is essential for food security and the future of humanity, vulnerable to impacts while at the same time decisive for building sustainable solutions.

This text shows how Brazilian science has pointed out ways to make production systems more resilient and efficient — both now and in the coming decades — in the face of pressures related to climate change. From adapting to extreme events to controlling greenhouse gas emissions, it documents practical solutions that have already been adapted in the Brazilian countryside. The book also addresses risk monitoring and presents innovative carbon balance techniques, demonstrating that it is possible to produce more and produce better, reconciling food production with the commitments of the global climate agenda.

This accessible and relevant content can serve as a reference for all readers who seek to understand and support pathways towards a sustainable future.



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