CHAPTER 1

Climate change and agriculture

Natural resources, geopolitics and science

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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.

Photo: Nasa/JPL

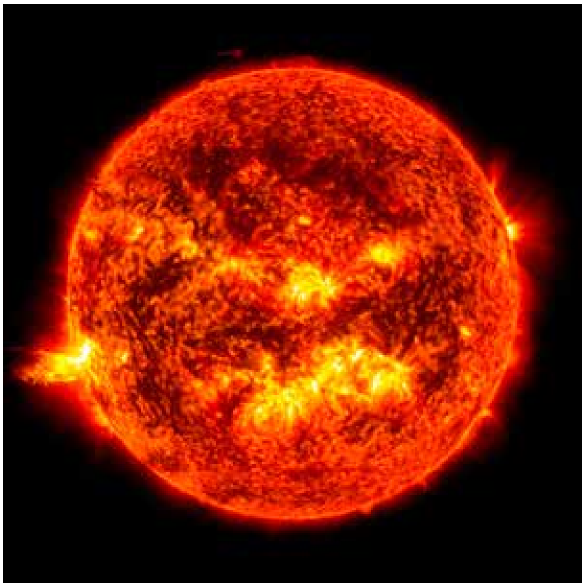

Figure 1.1. "A big ball of fire:" the Sun, the main source of energy for nearly everything that happens on Earth.

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.

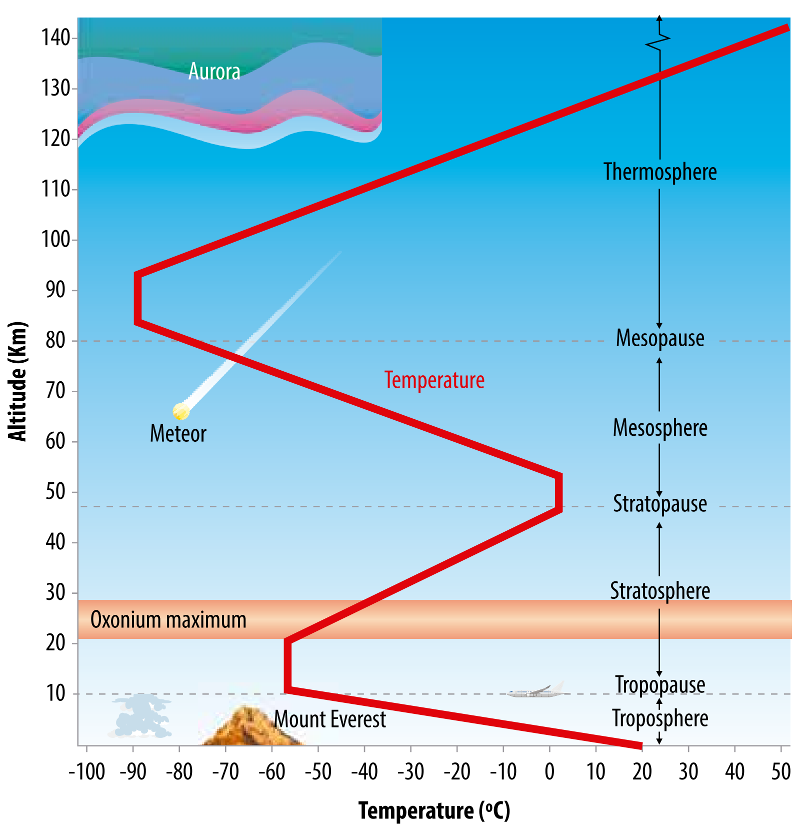

Figure 1.2. Atmospheric layers and temperature behavior as a function of interactions between solar radiation and the gases that make up the atmosphere.

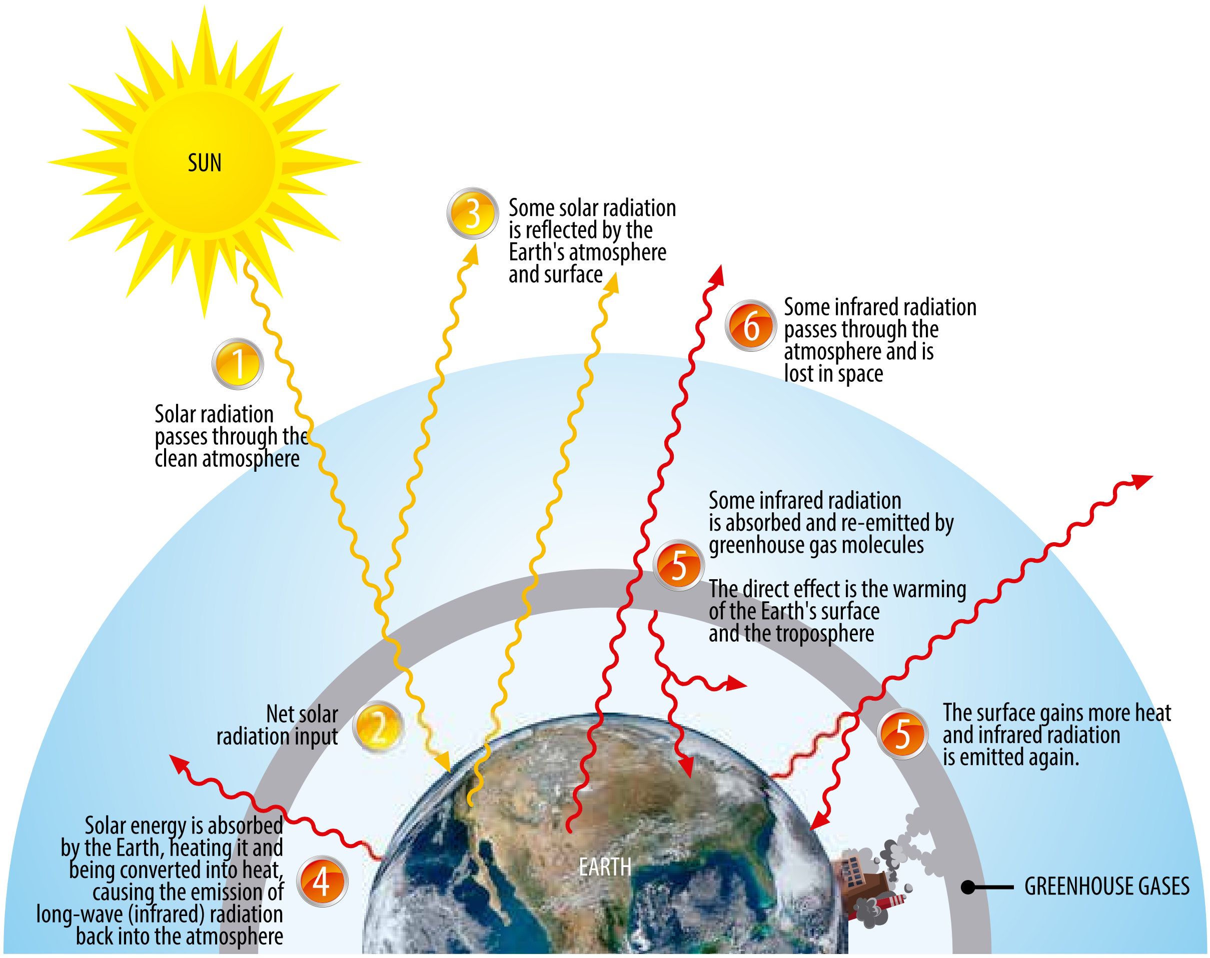

Figure 1.3. Interaction between solar radiation and the atmosphere and the natural greenhouse effect.

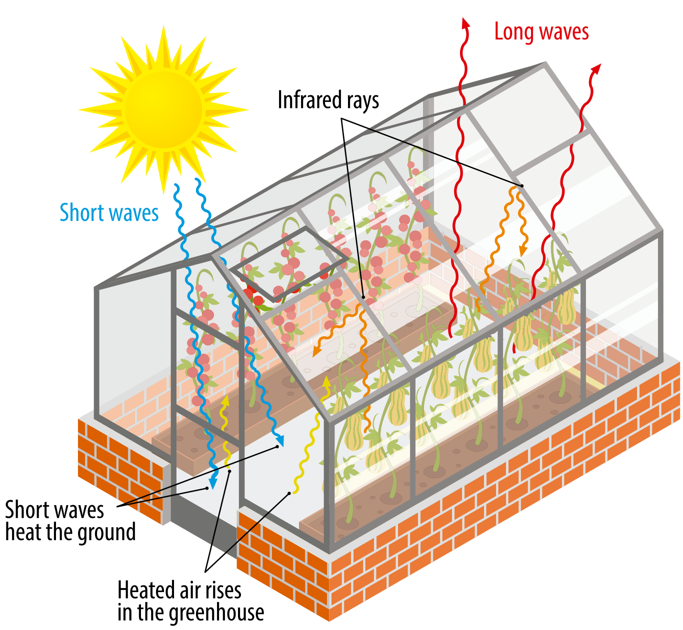

Figure 1.4. Interaction between radiation and internal heating in a glass greenhouse.

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, agriculture[1] 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

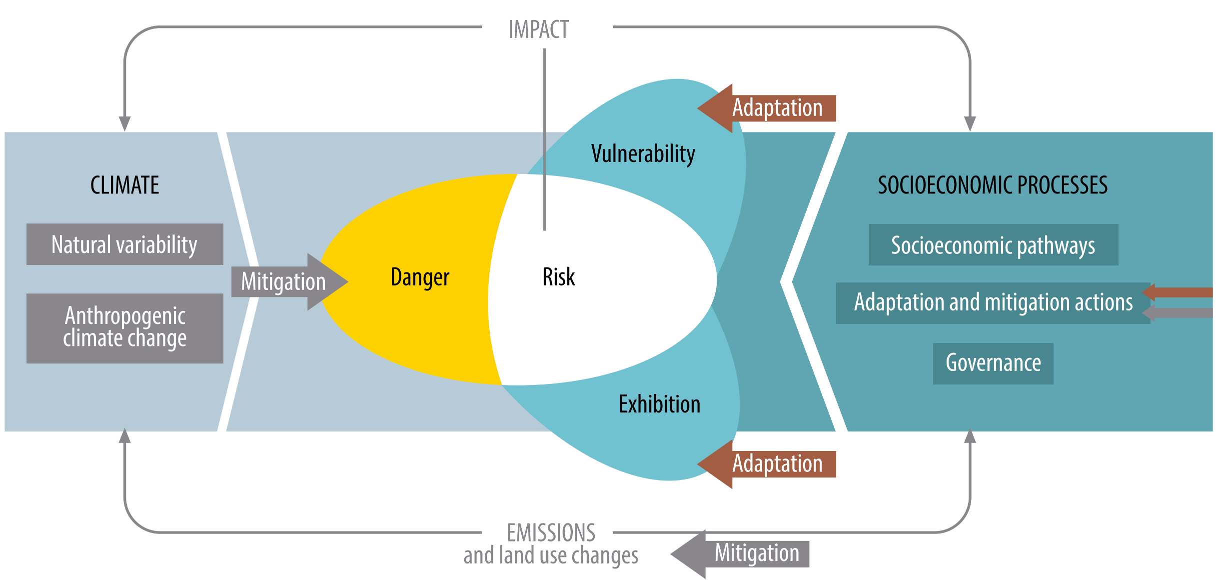

Figure 1.5. Climate change mitigation and adaptation efforts: risk components and the need for adaptation and mitigation activities according to the socio-economic pathways or development models adopted.

[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 n 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 emissions[3] 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 is 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 diplomacy[4] 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-intense 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
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> 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 system[5] 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,

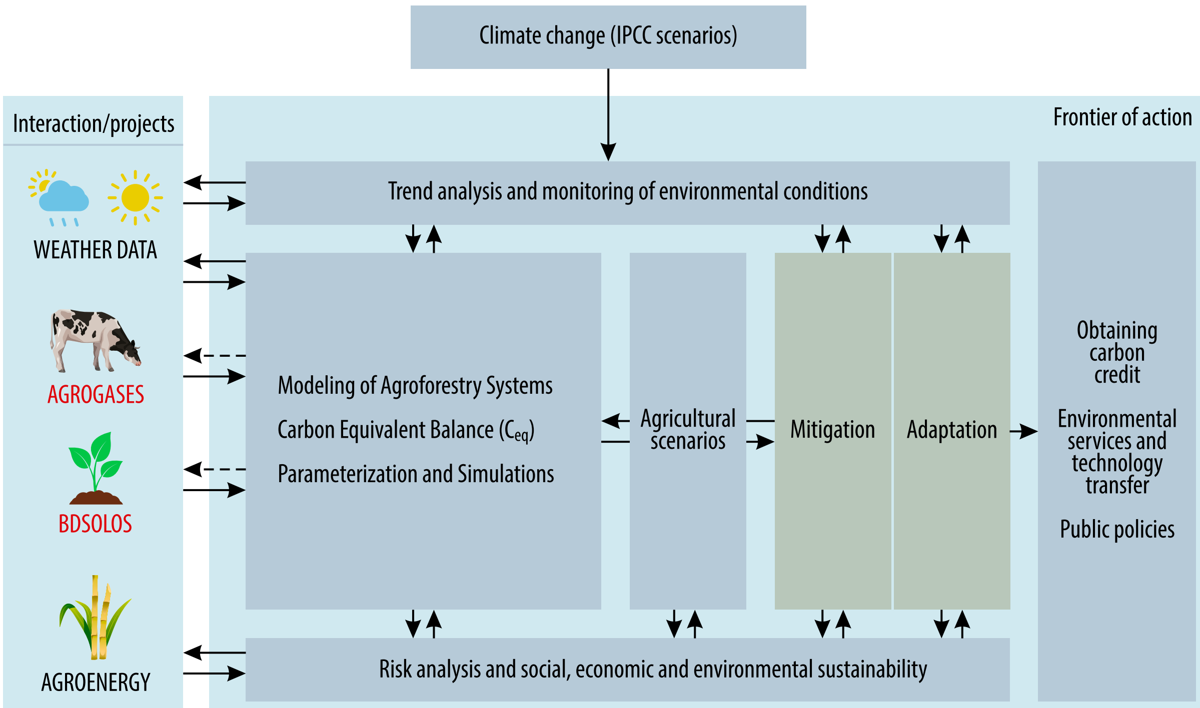


Figure 1.6. Embrapa's Climate Change Platform: structure, main elements and connections between elements.

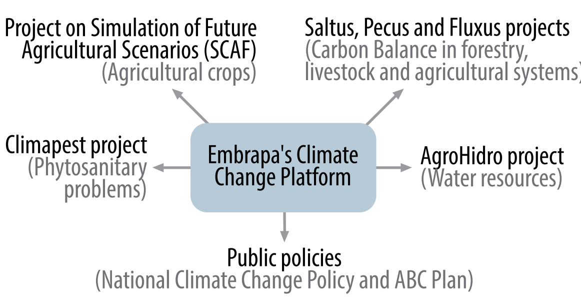


Figure 1.7. National-level projects linked to Embrapa's Climate Change Platform.

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 National 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: Portfolio 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

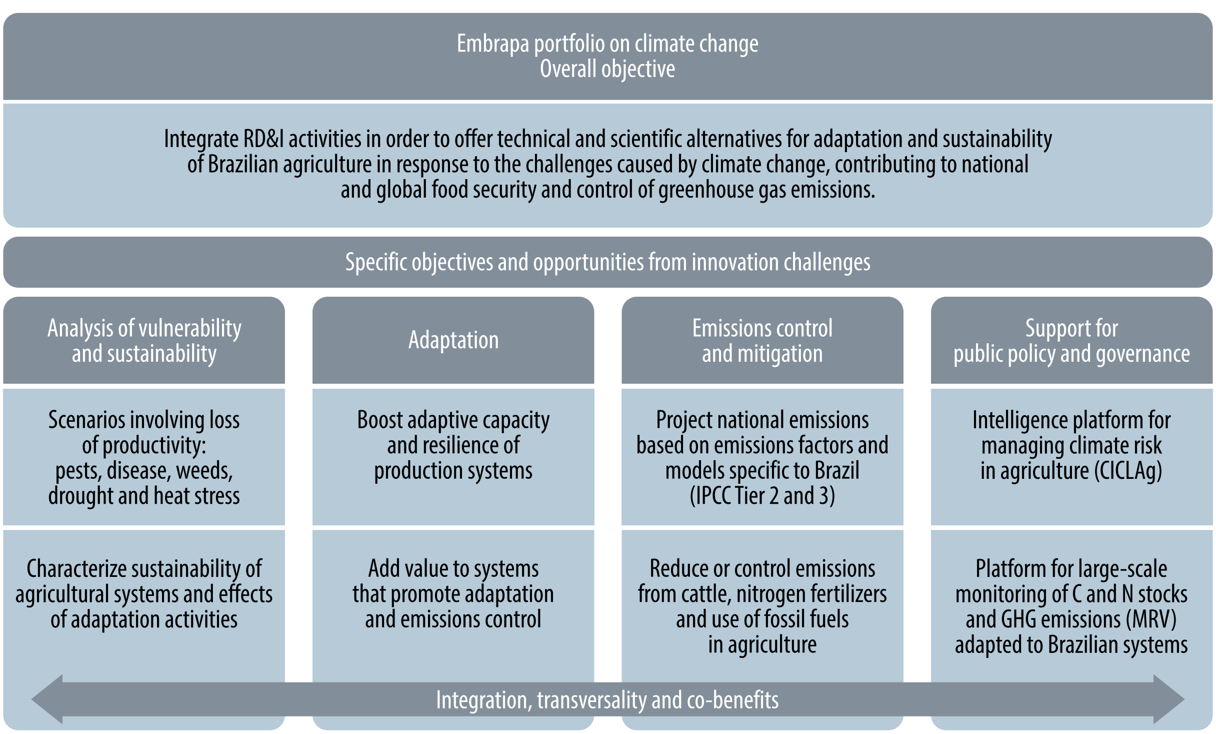


Figure 1.8. Objective and main characteristics of Embrapa's Climate Change Portfolio.

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,

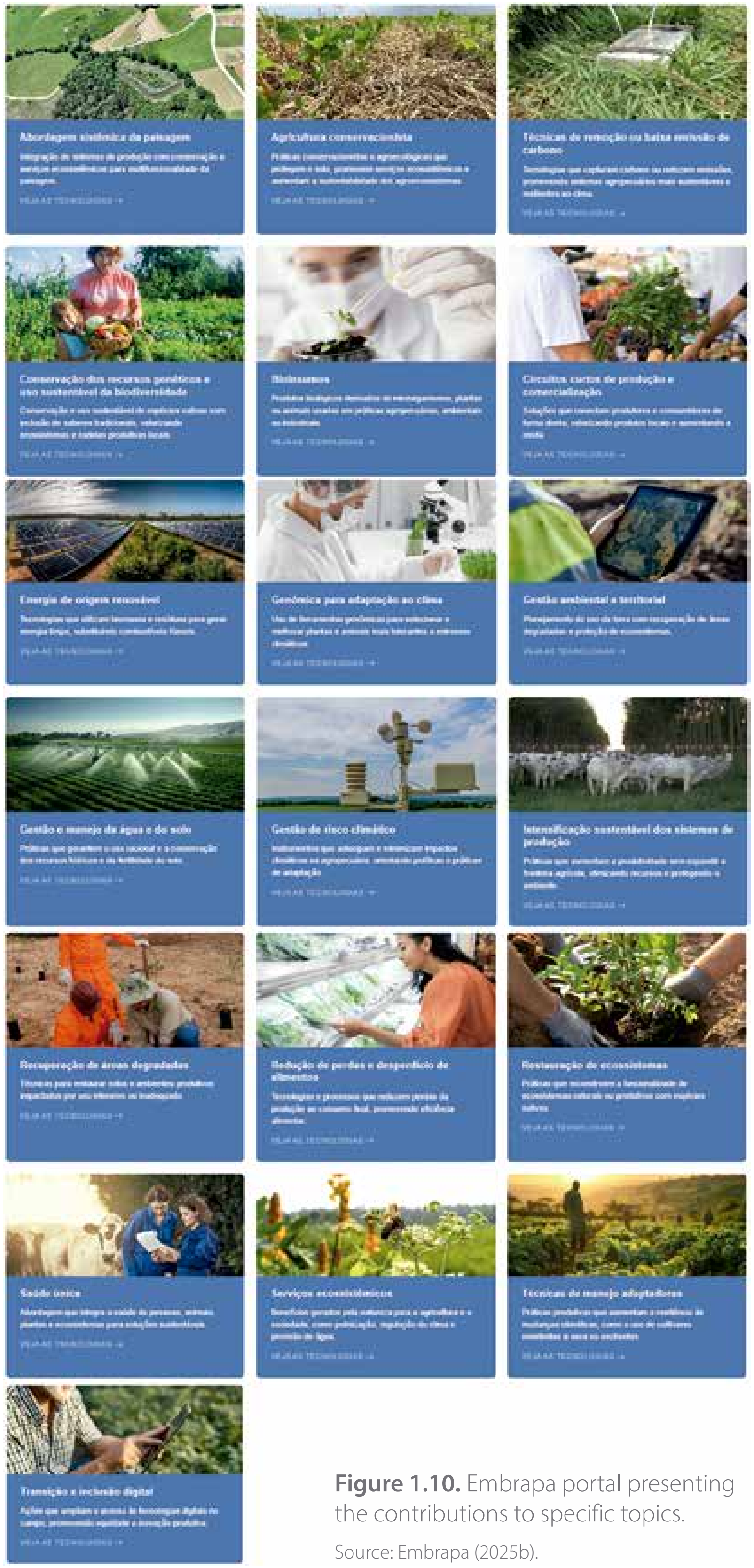


Figure 1.10. Embrapa portal presenting the contributions to specific topics.

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

Figure 1.11. Embrapa portal where solutions are presented by biome.

Source: Embrapa (2025c).

Figure 1.12. Word cloud containing Portuguese terms related to Embrapa's technological showcase for the 30th United Nations Conference on Climate Change (COP30). The most relevant terms include agriculture, improvement, livestock, production, carbon, family, genetics, management, soil, and animals.

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 healthfulness[7] 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.
- 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

[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.

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:

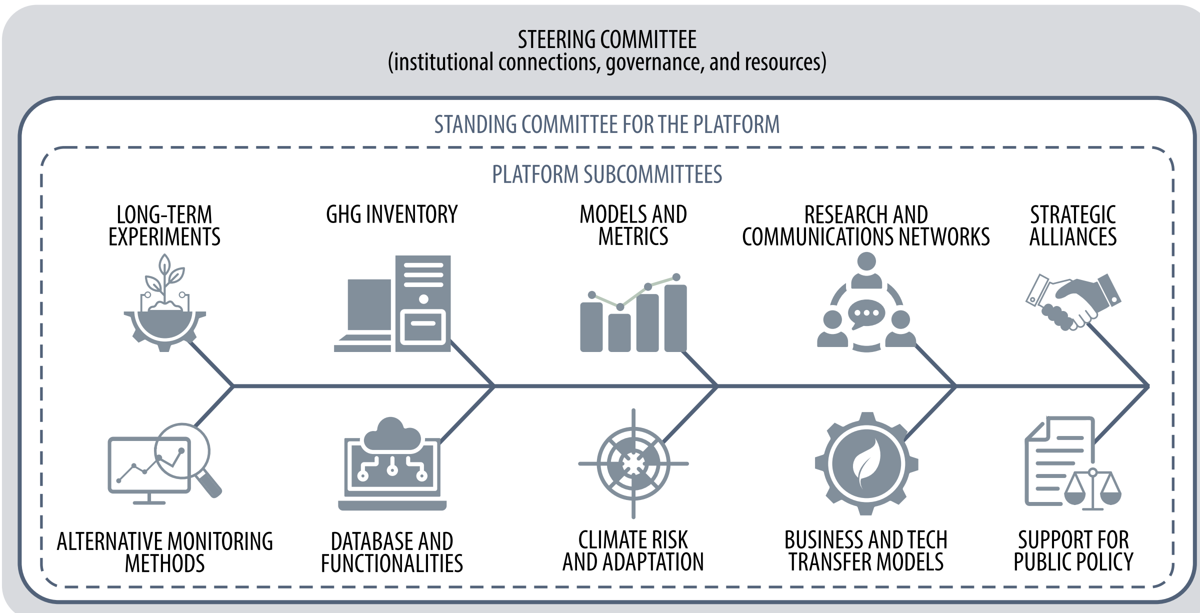
- Updating its research program.
- Management of corporate information and knowledge via a dedicated computing platform.
- Management of the structure and experimental and analytical protocols for long-term experiments.
- Developing quantification methods and techniques at different scales and for different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



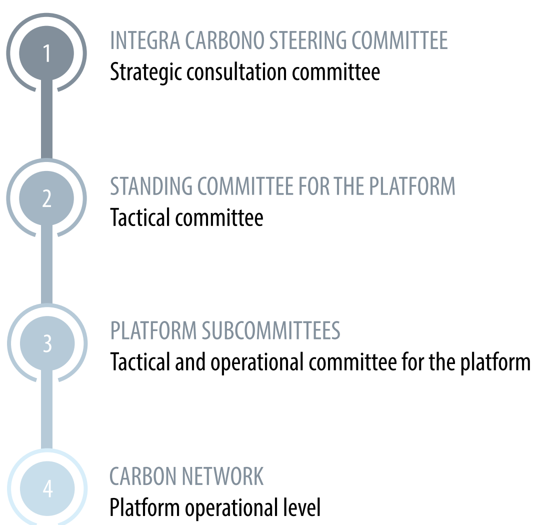


Figure 1.13. Relationship between the Steering Committee, the Standing Committee and the Subcommittees of the Embrapa Platform on Carbon Dynamics, Greenhouse Gases and Adaptation in Agriculture (CarbGEEAAg Platform), as part of the Integra Carbono Embrapa Initiative. Depicted below the box is the hierarchical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

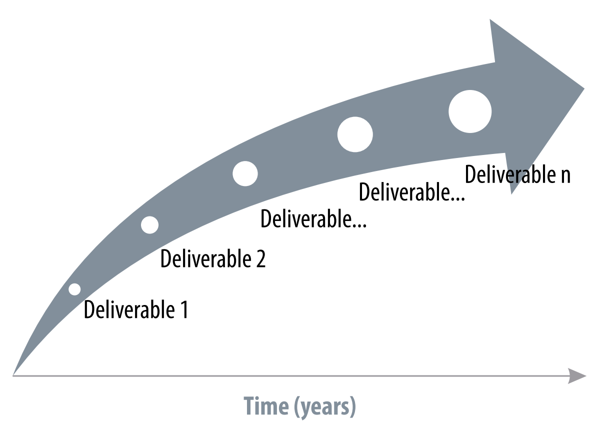


Figure 1. 14. Evolutionary and integrative rationale of the CarbGEEAAg Platform, with the production of deliverables over time.

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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