CHAPTER 6

Carbon accounting and life cycle assessment for Brazilian agricultural products

Marília Ieda da Silveira Folegatti – Roberto Giolo de Almeida – Alexandre Berndt – Maria Cléa Brito de Figueirêdo – Vanderlise Giongo – Álvaro Augusto Dossa – Rubens Sonsol Gondim – Renan Milagres Lage Novaes – Anna Leticia Montenegro Turtelli Pighinelli – Nilza Patrícia Ramos

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 metric[1] 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 processes[2] 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 system[3] 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 activities[6]) 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 grazing[9] in well-managed

[6] Service activities include green manure, cover crops, fallow land, etc.

[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 (CO_2), methane (CH_4), nitrous oxide (N_2O) 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 (CO_2) 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.

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 CO_2eq/kg carcass), while degraded pastures resulted in carbon footprints up to 25 times higher (50.3 kg CO_2eq/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 CO_2eq/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 CO_2eq/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 CO_2eq/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 CH_4 emissions by fixing carbon in tree trunks, resulting in a better balance between emissions and removals (-14.28 t CO_2 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 footprint[11] 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 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.

[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).

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).

- 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 CO_2 eq/kg, varying ± 0.36 kg CO_2 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).

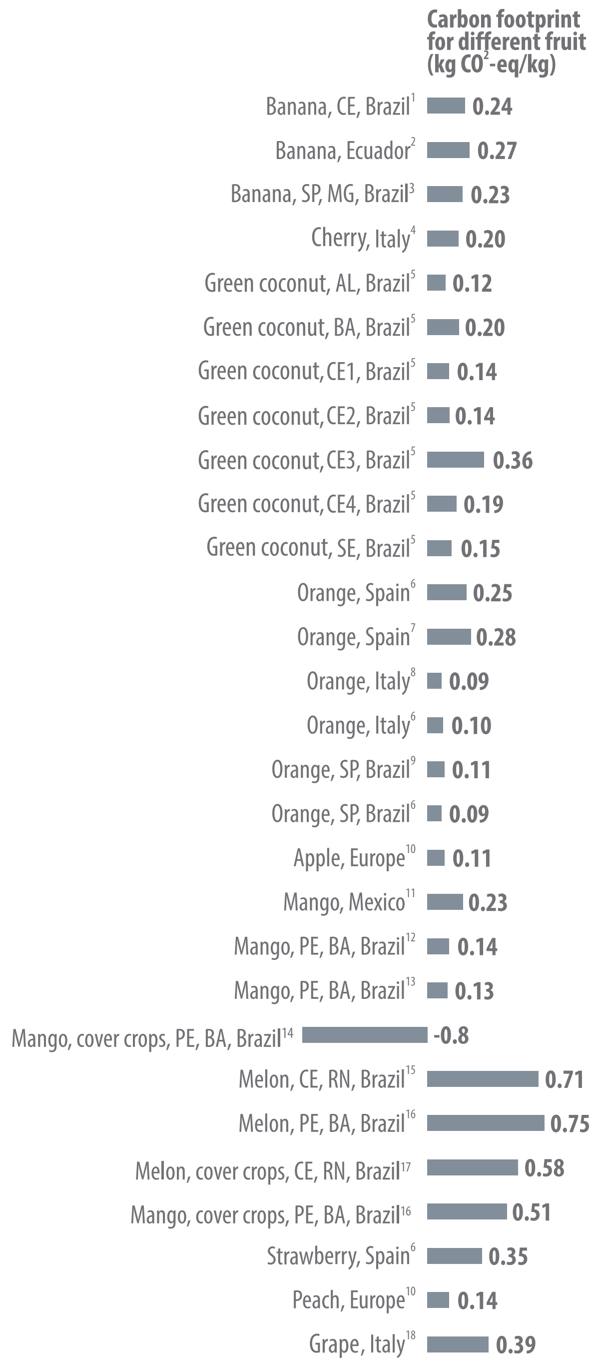


Figure 6.1. Comparison of the carbon footprint for different fruits produced in different countries and reported in various studies.

Note: These studies differed in the scope and year of the GHG emission and GWP factors.

Source: [1]Lima et al. (2024), [2]Roibás et al. (2016), [3]Coltro e Karaski (2019), [4]Tassieli et al. (2018), [5]Sampaio et al. (2021), [6]Mordini et al. (2009), [7]Ribal et al. (2019), [8]Giudice et al. (2013), [9]Knudsen et al. (2011), [10]Vinyes et al. (2017), [11]NMB (2010), [12]Basset-Mens et al. (2016), [13]Muller-Carneiro et al. (2018), [14]Dias et al. (2020), [15]Figueirêdo et al. (2013), [16]Santos et al. (2018), [17]Barros et al. (2019), [18]Marras 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 m^3-eq/kg) according to the location of irrigated production in the different river basins in Peru (Vázquez-Rowe et al., 2017).

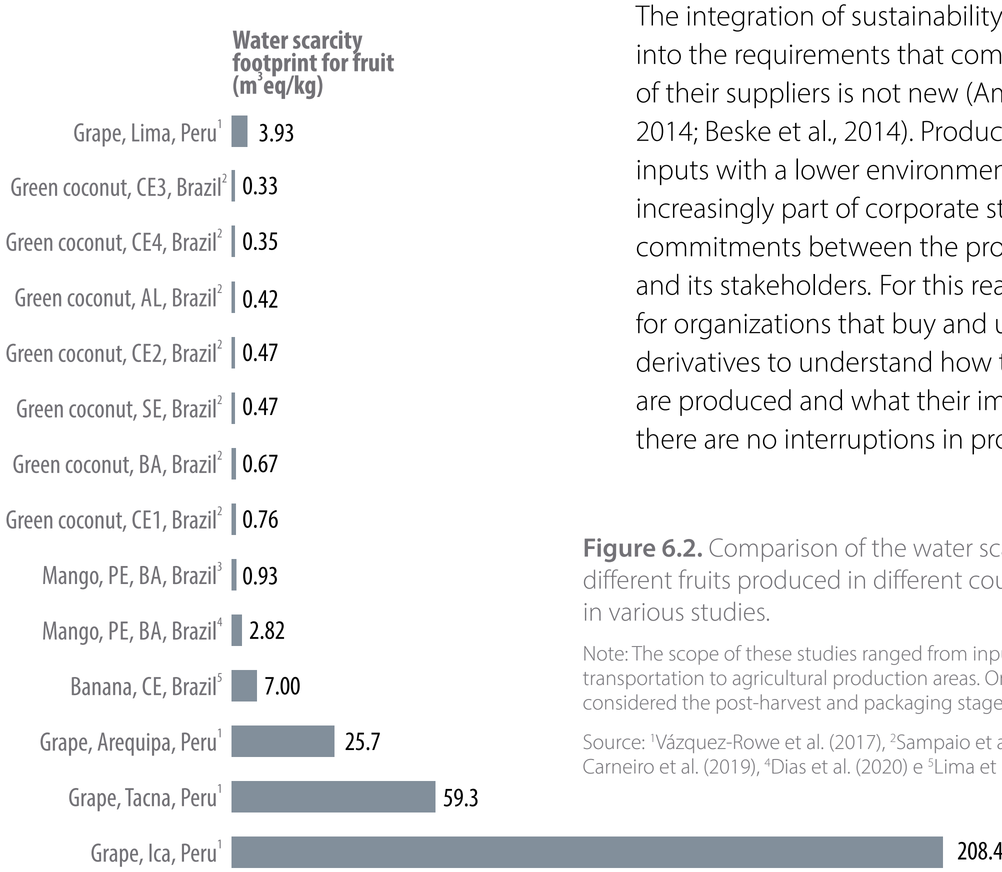


Figure 6.2. Comparison of the water scarcity footprint of different fruits produced in different countries and reported in various studies.

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: [1]Vázquez-Rowe et al. (2017), [2]Sampaio et al. (2021), [3]Muller-Carneiro et al. (2019), [4]Dias et al. (2020) e [5]Lima et al. (2024).

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, 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).

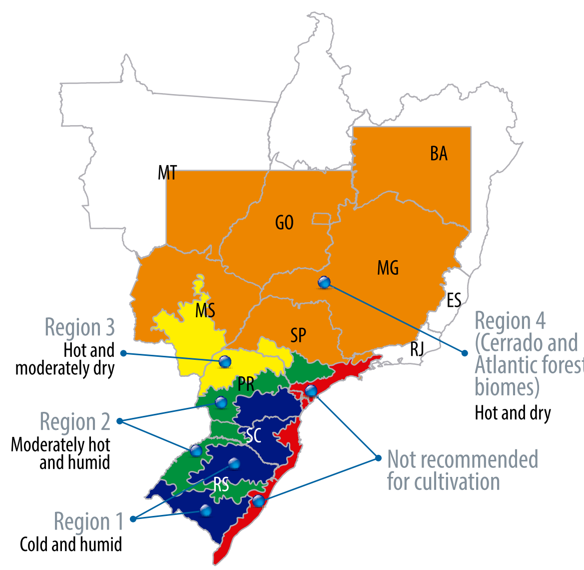


Figure 6.3. Homogeneous adaptation regions for wheat cultivars in Brazil.

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 (CO_2) 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, Ecoinvent[13] (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 Hestia[15] 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 Excel[17] (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 technosphere[19]) 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 CO_2eq/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 CO_2eq 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 CO_2eq.

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 CO_2eq/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 Entrepostos 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 CO_2eq/kg of melon for monocropping, and between 0.52 and 0.58 kg CO_2eq/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

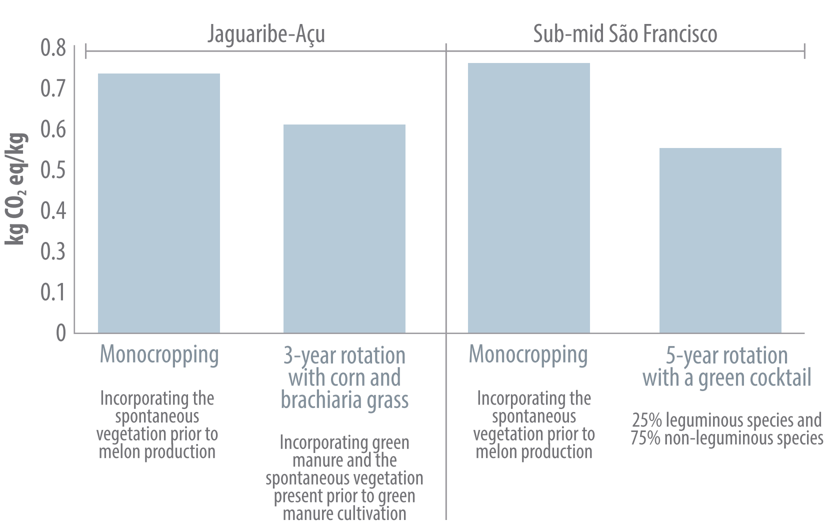


Figure 6.5. Carbon footprint of melons in a monocropping system and in rotation with green manures.

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

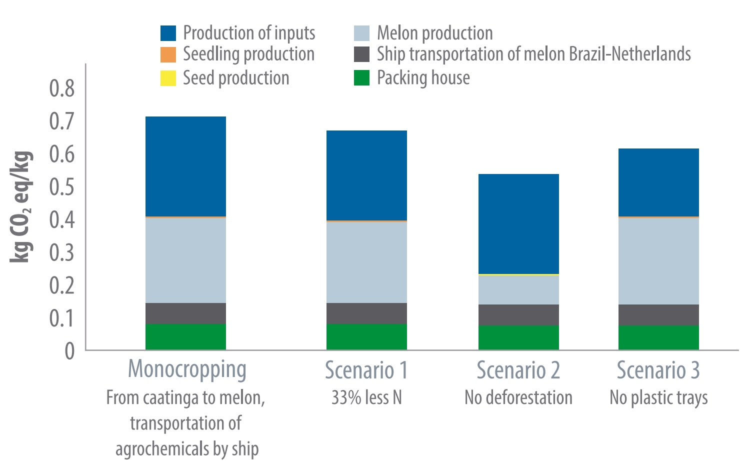


Figure 6.6. Analysis of scenarios that contribute to reducing the carbon footprint of monoculture melons in the Jaguaribe-Apodi region.

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 H_2Oeq/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 m^3/ha in any month — and requirement of this crop (2,700 m^3/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 H_2Oeq/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 CO_2eq/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 CO_2eq/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 CO_2eq/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 CO_2eq/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 m^3-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 m^3-eq/kg of mango (Dias et al., 2020), was higher than the value of 0.9 m^3-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 CO_2eq/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 m^3eq/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 m^3eq/kg) and the largest in Vaza Barris (0.62 m^3eq/kg); in Ceará, the highest value was recorded in the metropolitan basin (0.76 m^3eq/kg) and the lowest in Curu (0.33 m^3eq/kg); in Bahia, the largest footprint occurred in the Recôncavo Sul basin (0.67 m^3eq/kg) and the lowest in Itapicuru (0.19 m^3eq/kg); and in Alagoas, the São Miguel, Coruripe, and Piauí basins had the largest footprint (0.42 m^3eq/kg), while Camaragibe had the lowest (0.22 m^3eq/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 CO_2eq/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).

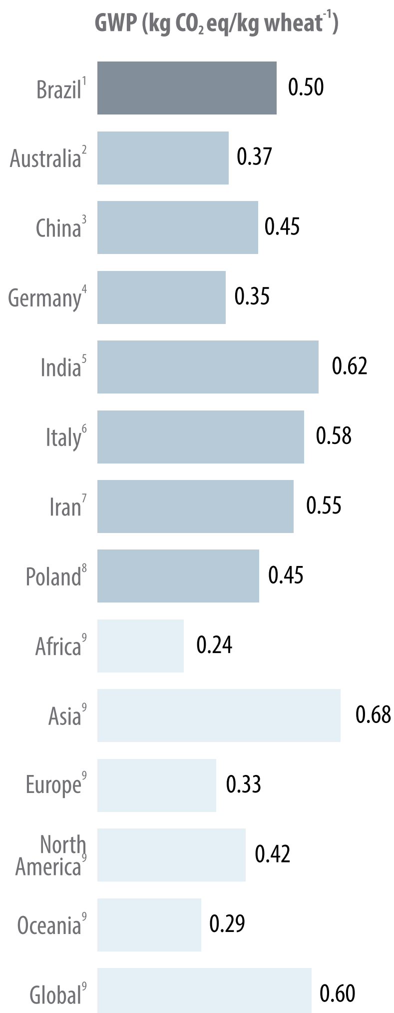


Figure 6.8. Comparison of the carbon footprint for production of 1 kg of wheat in different countries around the world.

Source: [1]Giongo et al. (2025); [2]Simmons et al. (2019); [3]Shao et al. (2024); [4]Riedesel et al. (2022); [5]Nayak et al. (2023); [6]Verdi et al. (2022); [7]Tahmasebi et al. (2018); [8]Pishgar-Komleh et al. (2020); [9]Feng 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-Giorsa 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 CO_2eq/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 CO_2eq/kg flour; Câmara Salim et al., 2020) and Italy (0.95 kg CO_2eq/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 CO_2eq/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 CO_2eq/kg of flour (Kulak et al., 2015).

The studies found that the carbon footprint varied between 0.48 and 1.66 kg CO_2eq/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.

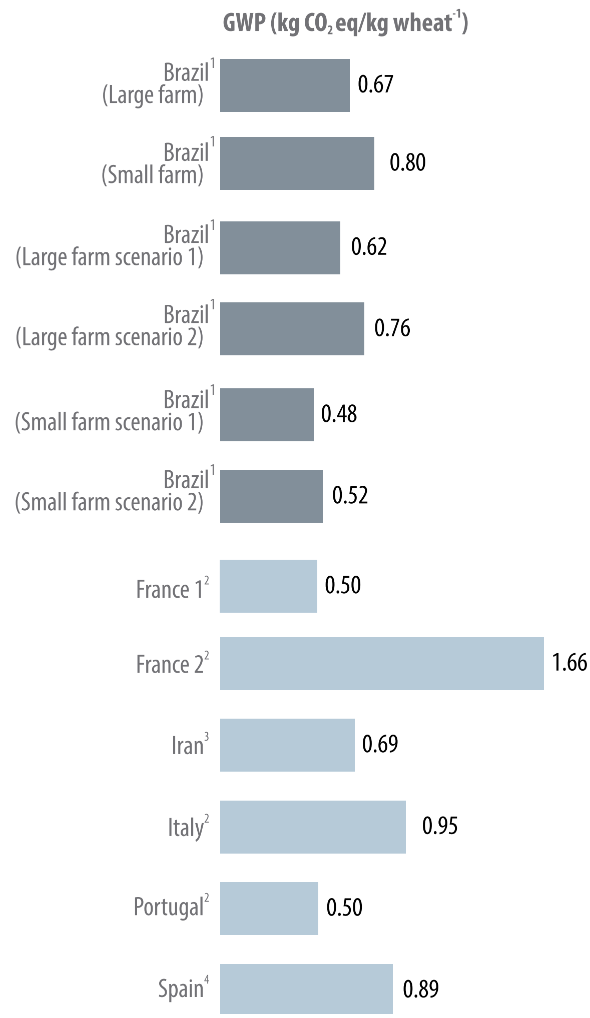


Figure 6.9. Comparison of the carbon footprint for production of 1 kg of wheat flour in Brazil and other countries.

Source: [1]Giongo et al. (2025); [2]Kulak et al. (2015); [3]Câmara Salim et al. (2020); [4]Pourmehdi and Kheiralipour (2020).

Life cycle assessment of wheat – other environmental impact categories

GWP, expressed in CO_2 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, eutrophication[21] 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 potential[22] 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.

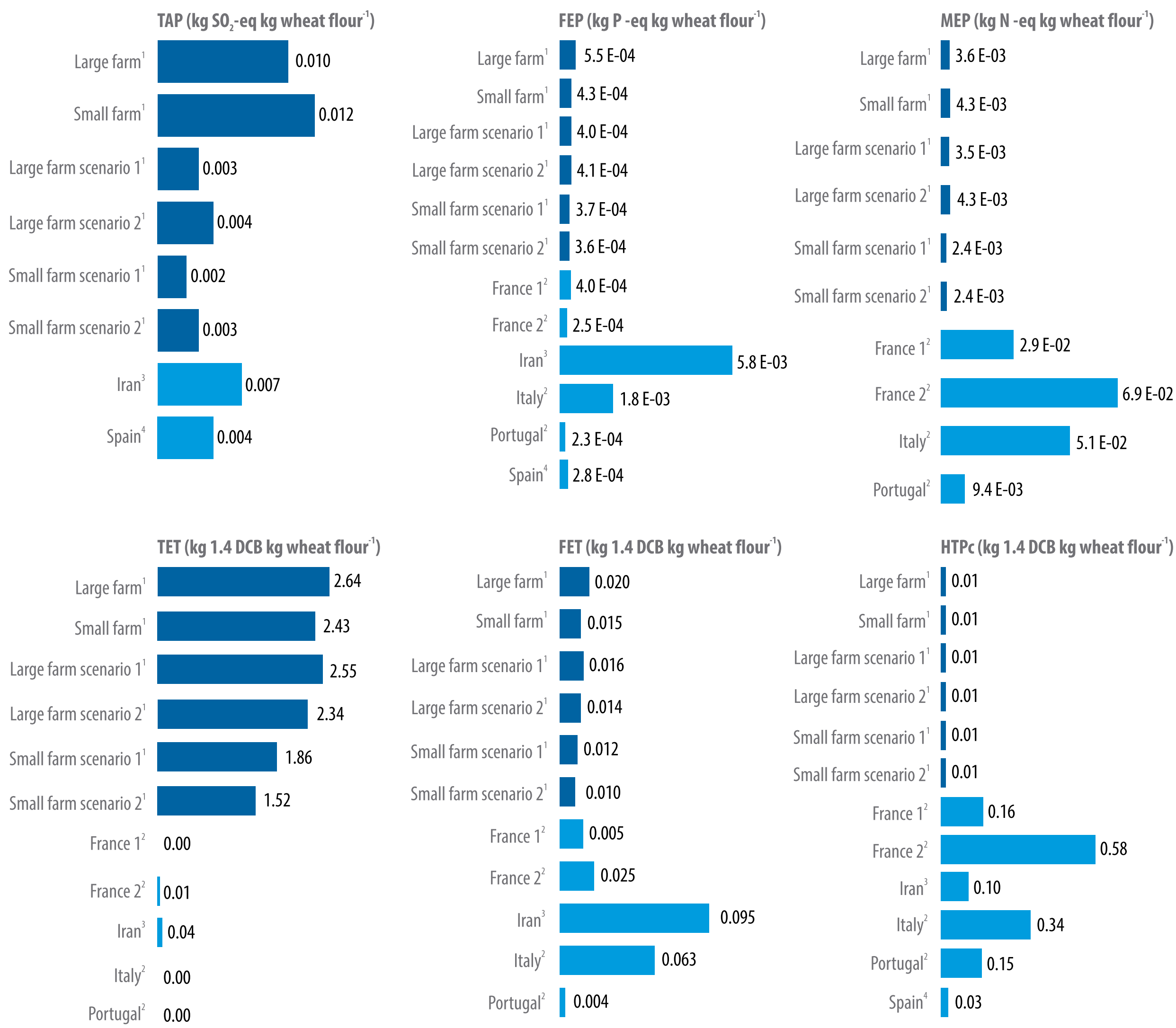


Figure 6.10. Comparison of environmental impact categories for the production of 1 kg of wheat flour in Brazil and other countries, in the current context and in proposed scenarios. TAP = terrestrial acidification potential; FEP = freshwater eutrophication potential; MEP = maritime eutrophication potential; TET = terrestrial ecotixicity; FET = freshwater ecotoxicity and HTPc = human toxicity potencial cancer.

Source: [1]Giongo et al. (2025); [2]Kulak et al. (2015); [3]Câmara Salim et al. (2020) and [4]Pourmehdi 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.

References

ACOSTA, A. da S.; RAMOS, M. Y. (ed.). **Lacunas de rendimento de grãos de trigo em áreas de atuação de cooperativas no Brasil**. Passo Fundo: Embrapa Trigo, 2021. 102 p. (Embrapa Trigo. Documentos, 197). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1135313. Accessed: 12 Jun. 2025.

ACOSTA, A. S. (ed.). **Dinâmica e cenário para a produção de trigo em áreas de atuação de cooperativas no Brasil**. Passo Fundo: Embrapa Trigo, 2018. 51 p. (Embrapa Trigo. Documentos, 179). Available at: http://www.infoteca.cnptia.embrapa.br/handle/doc/1096935. Accessed: 12 Jun. 2025.

AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS. **RenovaBio**. Brasília, DF, 2022. Available at: https://www.gov.br/anp/pt-br/assuntos/producao-e-fornecimento-de-biocombustiveis/renovabio. Accessed: 9 May 2025.

ALMEIDA, R. G.; ALVES, F. V. (ed.). **Diretrizes técnicas para produção de carne com baixa emissão de carbono certificada em pastagens tropicais**: carne baixo carbono (CBC). Campo Grande: Embrapa Gado de Corte, 2020. 36 p. (Embrapa Gado de Corte. Documentos, 280).

ALMEIDA, R. G.; MACEDO, M. C. M.; ARAÚJO, A. R. Soil carbon concentration and soil carbon stocks in integrated crop-livestock and crop-livestock-forestry systems in the Brazilian Cerrado: 14 years of establishment. In: INTERNATIONAL SYMPOSIUM ON INTEGRATED CROP-LIVESTOCK SYSTEMS, 4., 2023, Bento Gonçalves. **Proceedings** [...] Bento Gonçalves: Aliança SIPA, 2023. v. 1. p. 242-247.

AMINI, M.; BIENSTOCK, C. C. Corporate sustainability: An integrative definition and framework to evaluate corporate practice and guide academic research. **Journal of Cleaner Production**, v. 76, p. 12-19, maio 2014. DOI: 10.1016/j.jclepro.2014.02.016.

ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DO TRIGO. **Pesquisa de moagem de trigo 2022**: levantamento anual da moagem e produção de farinha no Brasil. São Paulo, 2023.

ASSOCIAÇÃO BRASILEIRA DOS PRODUTORES E EXPORTADORES DE FRUTAS E DERIVADOS. **Estatísticas**: painéis de produção e painéis de exportação. Brasília, DF, 2025. Available at: https://abrafrutas.org. Accessed: 6 Jul. 2025.

BARCELLOS, R.; GASQUES, J. G.; BASTOS, E. T. **Produtividade e empregos na agricultura**: o caso da soja no Brasil. Brasília, DF: Instituto de Pesquisa Econômica Aplicada, 2017. (Ipea. Texto para Discussão, n. 2317).

BARROS, V. S.; SANTOS, T. L.; FIGUEIRÊDO, M. C. B.; SILVA, E. O.; SOUSA, J. A.; ARAGÃO, F. A. S. Pegada de carbono de produtos agrícolas: estudo de caso do melão Amarelo. In: FIGUEIRÊDO, M. C. B; GONDIM, R. S.; ARAGÃO, F. A. S. (ed.). **Produção de melão e mudanças climáticas**: sistemas conservacionistas de cultivo para redução das pegadas de carbono e hídrica. Brasília, DF: Embrapa, 2017. p. 165-185.

BARROS, V. S.; SANTOS, T. L.; SILVA, E. O.; SOUSA, J. A.; FIGUEIRÊDO, M. C. B. Agronomic and environmental performance of melon produced in the Brazilian semiarid region. **Revista Caatinga**, v. 32, n. 4, p. 877-888, 2019.

BARSOTTI, M. P.; ALMEIDA, R. G.; MACEDO, M. C. M.; GOMES, R. C.; PALHARES, J. C. P.; MAZZETTO, A.; DICKHOEFER, U. A pathway for decreasing the water footprint from grazing-based beef production systems in the Tropics. **Agricultural Systems**, v. 222, 104192, 2025.

BARSOTTI, M. P.; ALMEIDA, R. G.; MACEDO, M. C. M.; LAURA, V. A.; ALVES, F. V.; WERNER, J.; DICKHOEFER, U. Assessing the freshwater fluxes related to beef cattle production: a comparison of integrated crop-livestock systems and a conventional grazing system. **Agricultural Water Management**, v. 269, 107665, 2022.

BARSOTTI, M. P.; ALMEIDA, R. G.; MACEDO, M. C. M.; ZAWADA, P.; WERNER, J.; DICKHOEFER, U. Behavioural responses of beef cattle to different grazing systems and the influence of these responses on water productivity of livestock in a tropical savannah. **Animal**, v. 18, n. 4, 101117, 2024.

BENETEL, G.; FAGUNDES, G. M.; MÉO-FILHO, P. de; SILVA, T. dos S.; WELTER, K. C.; MELO, F. A.; LOBO, A. A. G.; FRIGHETTO, R. T. S.; BERNDT, A.; MUIR, J. P.; BUENO, I. C. da S. Essential oils in nellore beef cattle: in vivo impact on rumen emissions. **Animals**, v. 14, n. 11, p. 1664, 2024.

BESKE, P.; LAND, A.; SEURING, S. Sustainable supply chain management practices and dynamic capabilities in the food industry: a critical analysis of the literature. **International Journal of Production Economics**, v. 152, n. 2, p. 131-143, 2014.

BLONK CONSULTANTS. **LUC impact tool**: full dataset: version 2021. Gouda, 2021. Available at: https://www.blonkconsultants.nl/en/tools/luc-impact-tool. Accessed: 12 Jun. 2025.

BOULAY, A.-M.; BARE, J; BENINI, L.; BERGER, M.; LATHUILLIÈRE, M. J.; MANZARDO, A.; MARGNI, M.; MOTOSHITA, M.; NÚÑEZ, M.; PASTOR, A. V.; RIDOUTT, B.; OKI, T.; WORBE, S.; PFISTER, S. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). **The International Journal Life Cycle Assessment**, v. 23, n. 2, p. 368-378, 2018.

BOULAY, A.-M.; PFISTER, S.; MOTOSHITA, M.; SCHENKER, U.; BENINI, L.; GHEEWALA, S. H.; FIGUEIRÊDO, M. C. B.; HARDING, K. Part 1: Water scarcity. In: FRISCHKNECHT, R.; JOLLIET, O. (ed.). **Global guidance for life cycle impact assessment indicators**. Paris: Unep, 2016. v. 1, p. 101-115.

BRANDÃO, M.; AZZI, E.; NOVAES, R. M.; COWIE, A. The modelling approach determines the carbon footprint of biofuels: the role of LCA in informing decision makers in government and industry. **Cleaner Environmental Systems**, v. 2, 100027, p. 1-8, 2021.

BRASIL. Ministério da Agricultura e Pecuária. **Setor de fruticultura que se destaca nas exportações brasileiras**. [Brasília, DF], 1 jul. 2024. Available at: https://www.gov.br/agricultura/pt-br/assuntos/noticias/setor-de-fruticultura-se-destaca-nas-exportacoes-brasileiras. Accessed: 1 May 2025.

BRASIL. Ministério da Agricultura, Abastecimento e Pecuária. **Plan for adaptation and low carbon emission in agriculture**: strategic vision for a new cycle. Brasília, DF, 2021. 25 p.

BRASIL. Ministério da Agricultura, Pecuária e Abastecimento. **Plano setorial de mitigação e de adaptação às mudanças climáticas para a consolidação de uma economia de baixa emissão de carbono na agricultura**: plano ABC (Agricultura de Baixa Emissão de Carbono). Brasília, DF, 2012. 173a p.

BRASIL. Ministério de Ciência, Tecnologia e Inovações. **Sistema de registro nacional de emissões (SIRENE)**. [Brasília, DF], 1 nov. 2022. Available at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/cgcl/paginas/sistema-de-registro-nacional-de-emissoes-sirene. Accessed: 9 May 2025.

BRENTON, P.; EDWARDS-JONES, G.; JENSEN, M. F. (ed.) **Carbon footprints and food systems**: do current accounting methodologies disadvantage developing countries? Washington, DC: World Bank Publications, 2021. 71 p.

BRITO, T.; FRAGOSO, R.; MARQUES, P.; FERNANDES-SILVA, A.; ARANHA, J. LCA of soybean supply chain produced in the state of Pará, located in the brazilian amazon biome. **Biology and Life Sciences Forum**, v. 3, n. 1, p. 11, 2021. DOI: https://doi.org/10.3390/IECAG2021-10072.

BRUNETTI, H. B.; OLIVEIRA, P. P. A.; PEZZOPANE, J. R. M.; BERNARDI, A. C. C.; GARCIA A. R.; BERNDT, A.; PEDROSO, A. F.; LELIS, A. L. J.; MEDEIROS, S. R. Silvopastoral system as a climate-smart alternative for beef production: enteric methane emission neutralization and animal thermal comfort increase. **Agricultural Systems**, v. 225, 104277, Apr. 2025.

BUDEL, J. C. de C.; CASTRO, V. C. G. de; SOUZA, S. M. de; NAHÚM, B. de S.; BARBOSA, A. V. C.; RODRIGUES, L. S.; BERNDT, A.; RENNÓ, L. N.; MORAIS, E. de; SILVA, J. A. R. da;

RODRIGUES, T. C. G. de C.; SILVA, A. G. M.; LOURENÇO-JUNIOR, J. de B. Methane emission, intake, digestibility, performance and blood metabolites in sheep supplemented with cupuassu and tucuma cake in the eastern Amazon. **Frontiers In Veterinary Science**, v. 10, 24 Apr. 2023. DOI: https://doi.org/10.3389/fvets.2023.1106619.

CALVO BUENDIA, E.; TANABE, K.; KRANJC, A.; BAASANSUREN, J.; FUKUDA, M.; NGARIZE, S.; OSAKO, A.; PYROZHENKO, Y.; SHERMANAU, P.; FEDERICI, S. (ed). **2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories**. [Geneva]: IPCC, 2019. Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/0_Overview/19R_V0_00_Cover_Foreword_Preface_Dedication.pdf. Accessed: 5 Oct. 2022.

CAMARA-SALIM, I.; ALMEIDA-GARCIA, F.; GONZALEZ-GARCIA, S.; ROMERO-RODRIGUEZ, A.; RUIZNOGUEIRAS, B.; PEREIRA-LORENZO, S.; FEIJOO, G.; MOREIRA, M. T. Life cycle assessment of autochthonous varieties of wheat and artisanal bread production in Galicia, Spain. **Science of The Total Environment**, v. 713, 136720, 2020. DOI: https://doi.org/10.1016/j.scitotenv.2020.136720.

CASTANHEIRA, E. G.; FREIRE, F. Greenhouse gas assessment of soybean production: implications of land use change and different cultivation systems. **Journal of Cleaner Production**, v. 54, n. 1, p. 49-60, 2013.

CASTRO, R. L.; CAIERÃO, E.; PIRES, J. L. F.; TOIGO, M. C.; AIRES, R. F.; ROSA, A. C.; TOMAZZI, D. J.; SANTOS, F. M.; CORASSA, G. M.; FACCO, G.; HORBE, T. A. N. Ensaio estadual de cultivares de trigo: safra 2021. In: REUNIÃO DA COMISSÃO BRASILEIRA DE PESQUISA DE TRIGO E TRITICALE, 15., 2022. **Atas e resumos** [...] Passo Fundo: Acervus, 2023. p. 220-224.

CAVALET-GIORSA, E.; GONZÁLEZ-MUÑOZ, A.; ATHIYANNAN, N.; HOLDEN, S.; SALHI, A.; GARDENER, C.; QUIROZ-CHÁVEZ, J.; RUSTAMOVA, S. M.; ELKOT, A. F.; PATPOUR, M.; RASHEED, A.; MAO, L.; LAGUDAH, E. S.; PERIYANNAN, S. K.; SHARON, A.; HIMMELBACH, A.; REIF, J. C.; KNAUFT, M.; MASCHER, M.; STEIN, N.; CHAYUT, N.; GHOSH, S.; PEROVIC, D.; PUTRA, A.; PERERA, A. B.; HU, C.-Y.; YU, G.; AHMED, H. I.; LAQUAI, K. D.; RIVERA, L. F.; CHEN, R.; WANG, Y.; GAO, X.; LIU, S.; RAUPP, W. J.; OLSON, E. L.; LEE, J.-Y.; CHHUNEJA, P.; KAUR, S.; ZHANG, P.; PARK, R. F.; DING, Y.; LIU, D.-C.; LI, W.; NASYROVA, F. Y.; DVORAK, J.; ABBASI, M.; LI, M.; KUMAR, N.; MEYER, W. B.; BOSHOFF, W. H. P.; STEFFENSON, B. J.; MATNY, O.; SHARMA, P. K.; TIWARI, V. K.; GREWAL, S.; POSNIAK, C. J.; CHAWLA, H. S.; ENS, J.; DUNNING, L. T.; KOLMER, J. A.; LAZO, G. R.; XU, S. S.; GU, Y. Q.; XU, X.; UAUY, C.; ABROUK, M.; BOUGOUFFA, S.; BRAR, G. S.; WULFF, B. B. H.; KRATTINGER, S. G. Origin and evolution of the bread wheat D genome. **Nature**, v. 633, p. 848-855, 2024. DOI: https://doi.org/10.1038/s41586-024-07808-z.

CHAGAS, J. H.; FRONZA, V.; SOARES SOBRINHO, J.; SUSSEL, A. A. B.; ALBRECHT, J. C. **Tecnologia de produção de trigo sequeiro no Cerrado do Brasil Central**. Passo Fundo: Embrapa Trigo, 2021. 101 p. Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1133483. Accessed: 12 Jun. 2025.

COMPRE RURAL**Bioinsumos e ambiciosa meta de dobrar a produção agrícola do Brasil**. 10 May 2023. Available at: https://www.comprerural.com/bioinsumos-e-ambiciosa-meta-de-dobrar-a-producao-agricola-do-brasil. Accessed: 12 Jun. 2025.

CONAB. **6º Levantamento**: safra [de Grãos] 2024/25. Brasília, DF, 2025a. Available at: https://www.gov.br/conab/pt-br/atuacao/informacoes-agropecuarias/safras/safra-de-graos/boletim-da-safra-de-graos/6o-levantamento-safra-2024-25/6o-levantamento-safra-2024-25. Accessed: 12 Jun. 2025.

CONAB. **Trigo**: histórico mensal: fevereiro 2025. Brasília, DF, 2025b. Available at: https://www.conab.gov.br/info-agro/analises-do-mercado-agropecuario-e-extrativista/analises-do-mercado/historico-mensal-de-trigo/item/download/53058_f5df7527d74b221dc5c67eb6070a1094. Accessed: 12 Jun. 2025.

CONGIO, G. F. I.; BANNINK, A.; MOGOLLÓN, O. L. M. Enteric methane mitigation strategies for ruminant livestock systems in the Latin America and Caribbean region: A meta-analysis. **Journal of Cleaner Production**, v. 312, 127693, 20 Aug. 2021.

DEFRIES, R. S.; FOLEY, J. A.; ASNER, G. P. Land-use choices: balancing human needs and ecosystem function. **Frontiers in Ecology and the Environment**, v. 2, n. 5, p. 249-257, Jun. 2004.

DENARDIN, J. E.; FAGANELLO, A.; LEMAINSKI, J. Converter plantio direto em Sistema Plantio Direto: um modelo à sustentabilidade agrícola. In: REUNIÃO DA COMISSÃO BRASILEIRA DE PESQUISA DE TRIGO E TRITICALE, 12., 2018, Passo Fundo. **Ata e resumos** [...] Passo Fundo: Projeto Passo Fundo, 2019. p. 568-572.

DIAS, A. F.; GIONGO, V.; BARROS, V. S.; MÜLLER-CARNEIRO, J.; FIGUEIRÊDO, M. C. B. An agile approach for evaluating the environmental-economic performance of cropping systems at experimental stage: the case of Brazilian mango. **The International Journal of Life Cycle Assessment**, v. 8, p. 1-17, 2020.

DINATO, R.; PICOLI, J. F.; FERNANDES, M.; KISS, B.; CHRYSSAFIDIS, J. **Pegada de carbono da carne bovina brasileira exportada para a união européia**: resultados e premissas para o cálculo das emissões do ciclo de vida do produto. São Paulo: Centro de Estudos em Sustentabilidade da Fundação Getulio Vargas, 2019. 151 p.

DONKE, A. C. G.; NOVAES, R. M. L.; PAZIANOTTO, R. A. A. Integrating regionalized Brazilian land use change datasets into the ecoinvent database: new data, premises and uncertainties have large effects in the results. **The International Journal of Life Cycle Assessment**, v. 25, p. 1027-1042, 20 May 2020.

DOSSA, A. A.; SANTI, A.; DALMAGO, G. A.; VIEIRA, O. V.; GIONGO, V. (ed.). **Programa Trigo Baixo Carbono**: um novo conceito de produção sustentável. Passo Fundo: Embrapa Trigo, 2023. 34 p. (Embrapa Trigo. Documentos, 206).

FARIAS, D. B. dos S.; RODRIGUES, L. N.; SANO, E. E.; MAGALHÃES, I. A. L. Atlas da agricultura irrigada no cerrado.

In: RODRIGUES, L. N. (ed.). **Agricultura irrigada no cerrado**: subsídios para o desenvolvimento sustentável. 2. ed. Brasília, DF: Embrapa, 2024. p. 469-503. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1165698/atlas-da-agricultura-irrigada-no-cerrado. Accessed: 12 Jun. 2025.

FENG, S.; LAKSHMANAN, P.; ZHANG, Y.; ZHANG, T.; LIANG, T.; WANG, W.; CHEN, X.; WANG, X. A comprehensive continental-scale analysis of carbon footprint of food production: Comparing continents around the world. **Journal of Cleaner Production**, v. 426, 138939, 2023. Available at: https://doi.org/10.1016/j.jclepro.2023.138939. Accessed: 12 Jun. 2025.

FIGUEIRÊDO, M. C. B.; DE BOER, I. J. M.; KROEZE, C.; BARROS, V. S.; SOUSA, J. A.; ARAGÃO, F.A.S.; GONDIM, R. S.; POTTING, J. Reducing the impact of irrigated crops on freshwater availability: the case of Brazilian yellow melons. **The International Journal of Life Cycle Assessment**, v. 19, p. 437-448, 2014.

FIGUEIRÊDO, M. C. B.; KROEZE, C.; POTTING, J.; BARROS, V. da S.; ARAGÃO, F. A. S. de; GONDIM, R. S.; SANTOS, T. de L.; BOER, I. J. M. de. The carbon footprint of exported Brazilian yellow melon. **Journal of Cleaner Production**, v. 47, p. 404-414, May 2013. DOI: https://doi.org/10.1016/j.jclepro.2012.09.015.

FOLEGATTI-MATSUURA, M. I. S.; CARDOSO, F. H.; PIGHINELLI, A. L. M. T.; MACIEL, V. G.; RAMOS, N. P.; GAROFALO, D. T.; MENDES, N. C.; MOORE, C. C. S.; NOVAES, R. M. L.; MORANDI, M. A. B. **ICVCalc**: ferramenta para construção de inventários agrícolas para estudos de avaliação de ciclo de vida. Jaguariúna: Embrapa Meio Ambiente, 2022. 47 p. (Embrapa Meio Ambiente. Circular técnica, 32).

FOLEGATTI-MATSUURAA, M. I. da S.; SILVA, O. R. R. F.; NOVAES, R. M. L.; PICOLI, J. F. Life cycle assessment of sisal produced in semiarid regions in Brazil. In: INTERNATIONAL CONFERENCE ON NATURAL FIBERS, 4., 2019, Porto. **Smart sustainable solutions**: book of abstracts. Minho: University of Minho, 2019. p. 416-417.

FONTES, H. R.; FERREIRA, J. M. S. (ed.). **A cultura do coco**. Brasília, DF: Embrapa Informação Tecnológica, 2006. 102 p. (Coleção Plantar, 48; Série Vermelha. Fruteiras). Available at: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/122591/1/00078970.pdf. Accessed: 24 Apr. 2025.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. **Environmental performance of large ruminant supply chains**: guidelines for assessment. Rome, 2015. 101 p. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/d5835b2f-b44a-43a0-884f-27c52e203b4e/content. Accessed: 9 May 2025.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. **FAO Terminology Portal**: life cycle assessment. Available at: https://www.fao.org/faoterm/viewentry/en/?entryId=178605. Accessed: 10 Jun. 2025.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. **Irrigation potential in Africa**: a basin approach. Rome: FAO Land and Water Development Division, 1997. (FAO Land and Water Bulletin, 4). Available at: https://www.fao.org/4/w4347e/w4347e00.htm. Accessed: 9 May 2025.

FÓRUM AMAZÔNIA SUSTENTÁVEL. **Pacto setorial da pecuária**. 15 out. 2008. Documento de compromisso entre empresas do setor e organizações socioambientais, organizado pelo Fórum Amazônia Sustentável e com Secretaria Executiva exercida pelo Instituto Ethos. Available at: https://akatu.org.br/pacto-setorial-da-pecuaria. Accessed: 12 Jun. 2025.

FURTADO, A. J. **Consórcio de feijão guandu com pastagens como estratégia de mitigação de gases de efeito estufa (GEE)**. 2022. 71 f. Dissertação (Mestrado em Nutrição e Produção Animal) – Faculdade de Medicina Veterinária e Zootecnia, Universidade de São Paulo, São Carlos.

FURTADO, A. J.; ABDALLA FILHO, A. L.; BRUNO, J. F.; PASQUINI NETO, R.; LOBO, A. A. G.; SILVA, G. V.; PERNA JÚNIOR, F.; ALVES, T. C.; BERNDT, A.; PEDROSO, A. F.; MEDEIROS, S. R.; OLIVEIRA, P. P. A.; RODRIGUES, P. H. M. Pigeon pea intercropped with tropical pasture as a mitigation strategy for enteric methane emissions of nellore steers. **Animals**, v. 13, n. 8, 1323, 2023. DOI: https://doi.org/10.3390/ani13081323.

GALUSNYAK, S. C.; PETRESCU, L.; SANDU, V.-C.; CORMOS, C.-C. Environmental impact assessment of green ammonia coupled with urea and ammonium nitrate production. **Journal of Environmental Management**, v. 343, 118215, 2023. DOI: https://doi.org/10.1016/j.jenvman.2023.118215.

GAROFALO, D. F. T.; NOVAES, R. M. L.; PAZIANOTTO, R. A. A.; MACIEL, V. G.; BRANDÃO, M.; SHIMBO, J. Z.; FOLEGATTI-MATSUURAA, M. I. S. Land-use change CO_2 emissions associated with agricultural products at municipal level in Brazil. **Journal of Cleaner Production,** v. 364, 132549, 2022.

GIONGO, V.; ACOSTA, A. da S.; DOSSA, A. A.; SANTI, A.; AMARAL, A. J. do; CAIERÃO, E.; DENARDIN, J. E.; VIEIRA, O. V.; FIGUEIRÊDO, M. C. B. de; FOLEGATTI, M. I. da S. F.; SAVIOLI, J. P. das D.; MARTINS, T. B.; SILVA, B. R.; PIRES, B. S.; SANTANA, M. da S. How can the environmental impacts of wheat cultivation and wheat flour production be reduced? A life cycle assessment of Brazilian wheat. **Journal of Cleaner Production**, v. 489, 144650, 2025.

GRAZIANO DA SILVA, J. **O novo rural brasileiro**. Campinas: Unicamp, 2004. 151 p.

GREENHOUSE GAS PROTOCOL**. Land sector and removals guidance**: part 1 accounting and reporting requirements and guidance: supplement to the GHG Protocol Corporate Standard and Scope 3 Standad: draft for pilot testing and review (september 2022). [S.l.]: World Resources Institute, 2022. 271 p. Available at: https://ghgprotocol.org/sites/default/files/2022-12/Land-Sector-and-Removals-Guidance-Pilot-Testing-and-Review-Draft-Part-1.pdf. Accessed: 20 May 2025.

HAN, W.; LIU, Y.; WANG, S.; FRAZ ALI, M.; MA, L.; LIN, X.; WANG, D. Adaptation progress and challenges of winter wheat breeding in China under climate warming. **Field**

Crops Research, v. 326, 109889, 2025. DOI: https://doi.org/10.1016/j.fcr.2025.109889.

HIRAKURI, M. H.; DEBIASI, H.; PROCÓPIO, S. de O.; FRANCHINI, J. C.; CASTRO, C. de. **Sistemas de produção**: conceitos e definições no contexto agrícola. Londrina: Embrapa Soja, 2012. 24 p. (Embrapa Soja. Documentos, 335).

HOEKSTRA, A. Y.; CHAPAGAIN, A. K.; ALDAYA, M. M.; MEKONNEN, M. M. **The water footprint assessment manual**: setting the global standard. London: Earthscan, 2011. 203 p.

HOMEM, B. G. C.; BORGES, L. P. C.; LIMA, I. B. G. de; GUIMARÃES, B. C.; SPASIANI, P. P.; FERREIRA, I. M.; MÉO FILHO, P.; BERNDT, A.; ALVES, B. J. R.; URQUIAGA, S.; BODDEY, R. M.; CASAGRANDE, D. R. Forage peanut legume as a strategy for improving beef production without increasing livestock greenhouse gas emissions. **Animal**, v. 18, n. 5, 101158, May 2024.

INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Produção agropecuária**. Available at: https://www.ibge.gov.br/explica/producao-agropecuaria/. Accessed: 1 May 2025.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 14040**: 2006: environmental management: life cycle assessment: principles and framework. Geneva, 2006a. Available at: https://www.iso.org/standard/37456.html. Accessed: 29 May 2025.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 14044**: 2006: environmental management: life cycle assessment: requirements and guidelines. Geneva, 2006b. Available at: https://www.iso.org/standard/38498.html. Accessed: 29 May 2025.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 14046**: 2014: environmental management: water footprint: principles: requirements and guidelines. Geneva, 2014. Available at: https://www.iso.org/standard/43263.html. Accessed: 29 May 2025.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. **ISO 14067**: 2018: greenhouse gases: carbon footprint of products: requirements and guidelines for quantification. Geneva, 2018. Available at: https://www.iso.org/standard/71206.html. Accessed: 29 May 2025.

IPCC. **2006 IPCC Guidelines for National Greenhouse Gas Inventories**: volume 4: agriculture, forestry and other land use. Eggborough: IGES, 2006. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4. Accessed: 12 Jun. 2025.

IPCC. **Climate change 2007**: synthesis report. Geneva, 2007. 104 p.

IPCC. **Climate change 2013**: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 2013. 1535 p. DOI: https://doi.org/10.1017/CBO9781107415324.

IPCC. **Climate change and land**: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Genebra, 2020. Available at: https://www.ipcc.ch/site/assets/uploads/sites/4/2020/02/SPM_Updated-Jan20.pdf. Accessed: 10 Jan. 2022.

IPCC. **Special report**: specail reporto n the ocean and cryosphere in a changing climate: glossary. Available at: https://www.ipcc.ch/srocc/chapter/glossary/?utm_source=chatgpt.com%20p%C3%A1gina%20697. Accessed: 12 Jun. 2025.

JACINTHO, M. A. C.; PROCOPIO, F. R.; ALVES, F. V.; ALMEIDA, R. G.; PIMENTA, S. C. **Diretrizes técnicas para produção de couro carbono neutro e couro baixo carbono**. São Carlos, SP: Embrapa Pecuária Sudeste, 2024. 20 p. (Embrapa Pecuária Sudeste. Documentos, 147).

KOCH, P.; SALOU, T. **AGRIBALYSE®**: rapport méthodologique-volet agriculture. Version 3.0; Version initiale 1.0;2014. Angers: Ed. Ademe, 2020. 319 p.

KULAK, M.; NEMECEK, T.; FROSSARD, E.; CHABLE, V.; GAILLARD, G. Life cycle assessment of bread from several alternative food networks in Europe. **Journal of Cleaner Production**, v. 90, p. 104-113, 2015. DOI: https://doi.org/10.1016/j.jclepro.2014.10.060.

LAM, W. Y.; CHATTERTON, J.; SIM, S.; KULAK, M.; MENDOZA BELTRAN, A.; HUIJBREGTS, M. A. J. Estimating greenhouse gas emissions from direct land use change due to crop production in multiple countries. **Science of The Total Environment**, v. 755, part 2, 143338, 2021. DOI: https://doi.org/10.1016/j.scitotenv.2020.143338.

LU, Y.; KRONZUCKER, H. J.; YU, H.; SHABALA, S.; SHI, W. Nitrogen-loss and carbon-footprint reduction by plant-rhizosphere exudates. **Trends in Plant Science**, v. 29, n. 4, p. 469-481, 2024. DOI: https://doi.org/10.1016/j.tplants.2023.09.007.

MACIEL, V. G.; ZORTEA, R. B.; DA SILVA, W. M.; CYBIS, L. F. D.; EINLOFT, S.; SEFERIN, M. Life Cycle Inventory for the agricultural stages of soybean production in the state of Rio Grande do Sul, Brazil. **Journal of Cleaner Production**, v. 93, p. 65-74, 2015.

MATSUURA, M. I. da S. F.; CARDOSO, F. H.; PIGHINELLI, A. L. M. T.; MACIEL, V. G.; RAMOS, N. P.; GAROFALO, D. F. T.; MENDES, N. C.; MOORE, C. C. S.; NOVAES, R. M. L.; MORANDI, M. A. B. **ICVCalc**: ferramenta para construção de inventários agrícolas para estudos de avaliação de ciclo de vida. Jaguariúna: Embrapa Meio Ambiente, 2022. 47 p. (Embrapa Meio Ambiente. Circular técnica, 32).

MATSUURA, M. I. da S. F.; PICOLI, J. F. **Life cycle inventories of agriculture, forestry and animal husbandry**: Brazil. Zurich: Ecoinvent Association, 2019. 143 p.

MATSUURA, M. I. da S. F.; SCACHETTI, M. T.; CHAGAS, M. F.; SEABRA, J. E. A.; MOREIRA, M. M. R.; BONOMI, A.; BAYMA, G.; PICOLI, J. F.; MORANDI, M. A. B.; RAMOS, N. P.; CAVALETT, O.; NOVAES, R. M. L. **RenovaCalcMD**: método e ferramenta para a contabilidade da intensidade de carbono de biocombustíveis no Programa RenovaBio. 2018. 58 p. Nota técnica. Available at: https://www.gov.br/anp/pt-br/assuntos/consultas-e-audiencias-publicas/consulta-audiencia-publica/2018/arquivos-consultas-e-audiencias-publicas-2018/cap-10-2018/cp10-2018_nota-tecnica-renova-calc.pdf. Accessed: 15 Jun. 2025.

MÉO FILHO, P.; BERNDT, A.; MARCONDES, C. R.; PEDROSO, A. F. ; SAKAMOTO, L. S.; VILAS BOAS, D. F. ; RODRIGUES, P. H. M. ; RIVERO, M. J. ; BUENO, I. C. S. Methane emissions, performance and carcass characteristics of different lines of beef steers reared on pasture and finished in feedlot. **Animals**, v. 10, n. 2, p. 303, 2020. DOI: https://doi.org/10.3390/ani10020303.

MÉO FILHO, P.; BERNDT, A.; PEZZOPANE, J. R. M.; PEDROSO, A. F.; BERNARDI, A. C. C.; RODRIGUES, P. H. M.; BUENO, I. C. S.; CORTE, R. R.; OLIVEIRA, P. P. A. Can intensified pasture systems reduce enteric methane emissions from beef zattle in the Atlantic Forest Biome? **Agronomy**, v. 12, n. 11, p. 2738, 2022. DOI: https://doi.org/10.3390/agronomy12112738.

MOREIRA, M. M. R.; NOVAES, R. M. L.; SCACHETTI, M. T.; CHAGAS, M. F.; SEABRA, J. E. A.; MATSUURA, M. I. da S. F.; RAMOS, N. P.; MORANDI, M. A. B.; BONOMI, A. Proposta de contabilização da mudança de uso da terra na política nacional de biocombustíveis (RenovaBio). In: CONGRESSO BRASILEIRO SOBRE GESTÃO DO CICLO DE VIDA, 6., 2018, Brasília, DF. **Anais [...]** Brasília, DF: Ibict, 2018. p. 155-161.

MORITA, A. M.; MOORE, C. C. S.; NOGUEIRA, A. R.; KULAY, L.; RAVAGNANI, M. A. S. Assessment of potential alternatives for improving environmental trouser jeans manufacturing performance in Brazil, **Journal of Cleaner Production**, v. 24, 119156, 2020. DOI: https://doi.org/10.1016/j.jclepro.2019.119156.

MOTTALEB, K. A.; GOVINDAN, V. How the ongoing armed conflict between Russia and Ukraine can affect the global wheat food security? **Frontiers in Food Science and Technology**, v. 3, 2023. DOI: https://doi.org/10.3389/frfst.2023.1072872.

MÜLLER CARNEIRO, J.; DIAS, A. F.; BARROS, V. D. S.; GIONGO, V.; FOLEGATTI, M. I. da S. F.; BRITO DE FIGUEIRÊDO, M. C. Carbon and water footprints of Brazilian mango produced in the semiarid region. **The International Journal of Life Cycle Assessment**, v. 24, n. 4, p. 735-752, 2019.

NAYAK, A. K.; TRIPATHI, R.; DEBNATH, M.; SWAIN, C. K.; DHAL, B.; VIJAYKUMAR, S.; NAYAK, A. D.; MOHANTY, S.; SHAHID, M.; KUMAR, A.; RAJAK, M.; MOHARANA, K. C.; CHATTERJEE, D.; MUNDA, S.; GURU, P. KHANAM, R.; LAL, B.; GAUTAM, P.; PATTANAIK, S.; SHUKLA, A. K.; FITTON, N.; SMITH, P.; PATHAK, H. Carbon and water footprints of major crop production in India. **Pedosphere**, v. 33, n. 3, p. 448-462, 2023. DOI: https://doi.org/10.1016/j.pedsph.2022.06.045.

NEMECEK, T.; BENGOA, X.; LANSCHE, J.; MOURON, P.; RIEDENER, E.; ROSSI, V.; HUMBERT, S. **Methodological guidelines for the life cycle Inventory of agricultural products**: version 3.0. Lausanne: World Food LCA Database (WFLDB), Quantis and Agroscop, 2015.

NEMECEK, T.; KÄGI, T. **Life cycle inventories of agricultural production systems**: Data v2.0 (2007). Zurich: ART, 2007. 46 p. (Ecoinvent Report, n. 15).

NEMECEK, T.; SCHNETZER, J. **Methods of assessment of direct field emissions for LCIs of agricultural production systems**: Data v3.0 (2012). Zurich: ART, 2011. 34 p.

NOVAES, R. M. L.; AMARAL, D. R.; MORANDI, M. A.; FOLEGATTI-MATSUURA, M. I. da S.; BRANDÃO, M. Comment on "The importance of GHG emissions from land use change for biofuels in Brazil: An assessment for current and 2030 scenarios". **Resources, Conservation and Recycling**, v. 201, n. 5, 107207, 2023.

NOVAES, R. M. L.; PAZIANOTTO, R. A. A.; BRANDÃO, M.; ALVES, B. J. R.; MAY, A.; FOLEGATTI-MATSUURA, M. I. da S. Estimating 20-year land-use change and derived CO2 emissions associated with crops, pasture and forestry in Brazil and each of its 27 states. **Global Change Biology**, v. 23, n. 9, p. 3716-3728, 2017.

NOVAES, R. M. L.; TUBIELLO, F. N.; GAROFALO, D. F. T.; DE SANTIS, G.; PAZIANOTTO, R. A. A.; FOLEGATTI-MATSUURA, M. I. da S. **Brazil's agricultural land, cropping frequency and second crop area**: FAOSTAT statistics and new estimates. Jaguariúna: Embrapa Environment, 2022. 25 p. (Embrapa Meio Ambiente. Boletim de Pesquisa e Desenvolvimento, 93).

OGLE, S. M.; WAKELIN, S. J.; BUENDIA, L.; MCCONKEY, B.; BALDOCK, J.; AKIYAMA, H.; KISHIMOTO, A. W. M.; CHIRINDA, N.; BERNOUX, M.; BHATTACHARYA, S.; CHUERSUWAN, N.; GOHEER, M. A. R.; HERGOUALC'H, K.; ISHIZUKA, S.; LASCO, R. D.; PAN, X.; PATHAK, H.; REGINA, K.; SATO, A.; VAZQUEZ-AMABILE, G.; WANG, C.; ZHENG, X. Cropland. In: BUENDIA, E. C.; TANABE, K.; KRANJC, A.; BAASANSUREN, J.; FUKUDA, M.; NGARIZE, S.; OSAKO, A.; PYROZHENKO, Y.; SHERMANAU, P.; FEDERICI, S. (ed.). **2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories**. Hayama: IPCC, 2019. v. 4, p. 5.1-5.102. Available at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch05_Cropland.pdf. Accessed: 20 Oct. 2021.

OLIVEIRA, P. P. A.; BERNARDI, A. C. C.; PEZZOPANE, J. R. M.; BOSI, C.; PERNA JÚNIOR, F.; TADINI, A. M.; MARTIN-NETO, L.; RODRIGUES, P. H. M. Potential of integrated trees-pasture-based systems for GHG emission mitigation and improving soil carbon dynamics in the Atlantic forest biome, Southeastern of Brazil. **European Journal of Agronomy**, v. 158, n. 32, 127219, 2024. DOI: https://doi.org/10.1016/j.eja.2024.127219.

OLIVEIRA, P. P. A.; BERNDT, A.; PEDROSO, A. de F.; ALVES, T. C.; LEMES, A. P.; OLIVEIRA, B. A.; PEZZOPANE, J. R. M.; RODRIGUES, P. H. M. Greenhouse gas balance and mitigation of pasture-based dairy production systems in the Brazilian Atlantic Forest biome. **Frontiers in Veterinary Science**, v. 9, p. 1-15, 2022. DOI: https://doi.org/10.3389/fvets.2022.958751.

OLIVEIRA, P. P. A.; BERNDT, A.; PEDROSO, A. F.; ALVES, T. C.; PEZZOPANE, J. R. M.; SAKAMOTO, L. S.; HENRIQUE, F. L.; RODRIGUES, P. H. M. Greenhouse gas balance and carbon footprint of pasture-based beef cattle production systems in the tropical region (Atlantic Forest biome). **Animal**, v. 14, p. 427-437, 2020. Supplement 3.

PASINATO, A.; CUNHA, G. R. da; FONTANA, D. C.; MONTEIRO, J. E. B. de A.; NAKAI, A. M.; OLIVEIRA, A. F. de. Área potencial e limitações para a expansão de trigo de sequeiro no bioma Cerrado do Brasil Central. **Pesquisa Agropecuária Brasileira**, v. 53, n. 7, p. 779-790, 2018.

PENA-BERMUDEZ, Y. A.; VINCENZI, R.; MEO-FILHO, P.; SAKAMOTO, L. S.; LOBO, R.; BENETEL, G.; LOBO, A.; MATOS, C.; BENETEL, V.; LIMA, C. G.; BERNDT, A.; CARDENAS, L. M.; BUENO, I. C. S. Effect of yerba mate extract as feed additive on ruminal fermentation and methane emissions in beef cattle. **Animals**, v. 12, n. 21, p. 2997, 2022.

PISHGAR-KOMLEH, S. H.; ZYLOWSKI, T.; ROZAKIS, S.; KOZYRA, J. Efficiency under different methods for incorporating undesirable outputs in an LCA+DEA framework: a case study of winter wheat production in Poland. **Journal of Environmental Management**, v. 260, 110138, 2020. DOI: https://doi.org/10.1016/j.jenvman.2020.110138.

POORE, J.; NEMECEK, T. Reducing food's environmental impacts through producers and consumers. **Science**, v. 360, n. 6392, p. 987-992, 2018.

POURMEHDI, K., KHEIRALIPOUR, K., 2020. Assessing the effects of wheat flour production on the environment. **Advances in Environmental Technology**, v. 6, n. 2, p. 111-117, 2020. DOI: https://doi.org/10.22104/aet.2021.4704.1280.

REUNIÃO DA COMISSÃO BRASILEIRA DE PESQUISA DE TRIGO E TRITICALE (15. : 2022 : Brasília, DF). **Informações técnicas para trigo e triticale**: safra 2023. Brasília, DF: Embrapa, 2023. 142 p.

RIDOUTT, B. G.; PFISTER, S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. **Global Environmental Change**, v. 20, n. 1, p. 113-120, 2010.

RIEDESEL, L.; LAIDIG, F.; HADASCH, S.; RENTEL, D.; HACKAUF, B.; PIEPHO, H. P.; FEIKE, T. Breeding progress reduces carbon footprints of wheat and rye. **Journal of Cleaner Production**, v. 377, 134326, 2022. DOI: https://doi.org/10.1016/j.jclepro.2022.134326.

SAMPAIO, A. P. C.; SILVA, A. K. P.; AMORIM, J. R. de; SANTIAGO, A. D.; MIRANDA, F. R. de; BARROS, V. S.; SALES, M. C. L.; FIGUEIRÊDO, M. C. B. de. Reducing the carbon and water footprints of Brazilian green coconut. **The International Journal of Life Cycle Assessment**, v. 26, n. 4, p. 707-723, 2021.

SANTOS, T. L.; NUNES, A. B. A.; GIONGO, V.; BARROS, V. S.; FIGUEIRÊDO, M. C. B. Cleaner fruit production with green manure: the case of brazilian melons. **Journal of Cleaner Production**, v. 181, p. 260-270, 2018.

SHAO, G.; ZHOU, J.; LIU, B.; ALHARBI, S. A.; LIU, E.; KUZYAKOV, Y. Carbon footprint of maize-wheat cropping system after 40-year fertilization. **Science of the Total Environment**, v. 926, 172082, 2024. DOI: https://doi.org/10.1016/j.scitotenv.2024.172082.

SHUKLA, P. R.; SKEA, J. (ed.). **Climate change 2022**: mitigation of climate change: working group III contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change. [Cambridge]: Cambridge University Press, 2022. 2029 p.

SILVA, C. B.; VALENTE, L. M.; MATOS, E.; BRANDÃO, M.; NETO, B. Life cycle assessment of aquafeed ingredients. **The International Journal of Life Cycle Assessment**, v. 23, n. 5, p. 995-1017, 2018.

SIMMONS, A. T.; MURRAY, A.; BROCK, P. M.; GRANT, T.; COWIE, A. L.; EADY, S.; SHARMA, B. Life cycle inventories for the Australian grains sector. **Crop & Pasture Science**, v. 70, n. 7, p. 575-584, 2019. DOI: https://doi.org/10.1071/CP18412.

SOBEL, T. F.; COSTA, E. de F. Impactos na geração de empregos e renda da implantação do projeto pontal no Vale do São Francisco. **Revista Econômica do Nordeste**, v. 35, n. 3, p. 405-423, 2004. DOI: https://doi.org/10.61673/ren.2004.794.

TAHMASEBI, M.; FEIKE, T.; SOLTANI, A.; RAMROUDI, M.; HA, N. Trade-off between productivity and environmental sustainability in irrigated vs. rainfed wheat production in Iran. **Journal of Cleaner Production**, v. 174, p. 367-379, 2018. DOI: https://doi.org/10.1016/j.jclepro.2017.10.305.

THE EUROPEAN FEED MANUFACTURERS' FEDERATION. **The PEFCR feed for food producing animals**. [S.l.]: FEFAC, 2024. Available at: https://fefac.eu/priorities/sustainability/pefcr-feed/. Accessed: 29 May 2025.

TUBIELLO, F. N.; ROSENZWEIG, C.; CONCHEDDA, G.; KARL, K.; GÜTSCHOW, J.; XUEYAO, P.; OBLI-LARYEA, G.; WANNER, N.; QIU, S. Y.; BARROS, J de.; FLAMMINI, A.; MENCOS-CONTRERAS, E.; SOUZA, L.; QUADRELLI, HEIÐARSDÓTTIR, H. H.; BENOIT, P.; HAYEK, M.; SANDALOW, D. Greenhouse gas emissions from food systems: building the evidence base. **Environmental Research Letters**, v. 16, n. 6, 2021. DOI: https://doi.org/10.1088/1748-9326/ac018e.

VAN PAASSEN, M.; BRACONI, N.; KULING, L.; DURLINGER, B.; GUAL, P. **Agri-footprint 5.0**. Gouda: Mérieux NutriSciences, 2019. 134 p. Available at: https://www.agri-footprint.com/wp-content/uploads/2019/11/Agri-Footprint-5.0-Part-2-Description-of-data-17-7-2019-for-web.pdf. Accessed: 20 Apr. 2025.

VÁZQUEZ-ROWE, I.; TORRES-GARCÍA, J. R.; CÁCERES, A. L.; LARREA-GALLEGOS, G.; QUISPE, I.; KAHHAT, R. Assessing the magnitude of potential environmental impacts related to water and toxicity in the Peruvian hyper-arid coast: a case study for the cultivation of grapes for *pisco* production. **Science of the Total Environment**, v. 601-602, p. 532-542, 2017.

VERDI, L.; DALLA MARTA, A.; FALCONI, F.; ORLANDINI, S.; MANCINI, M. 2022. Comparison between organic and conventional farming systems using Life Cycle Assessment (LCA): a case study with an ancient wheat variety. **European Journal of Agronomy**, v. 141, 126638, 2022. DOI: https://doi.org/10.1016/j.eja.2022.126638.

WANG, H.; MA, S.; SHAO, G.; DITTERT, K. Use of urease and nitrification inhibitors to decrease yield-scaled N_2O emissions from winter wheat and oilseed rape fields: a two-year field experiment. **Agriculture, Ecosystems & Environment**, v. 319, 107552, 2021. DOI: https://doi.org/10.1016/j.agee.2021.107552.

XIONG, W.; REYNOLDS, M. P.; MONTES, C.; CROSSA, J.; SNAPP, S.; AKIN, B.; MESUT, K.; OZDEMIR, F.; LI, H.; HE, Z.; WANG, D.; CHEN, F. New wheat breeding paradigms for a warming climate. **Nature Climate Change**, v. 14, p. 869-875, 2024. DOI: https://doi.org/10.1038/s41558-024-02069-0.

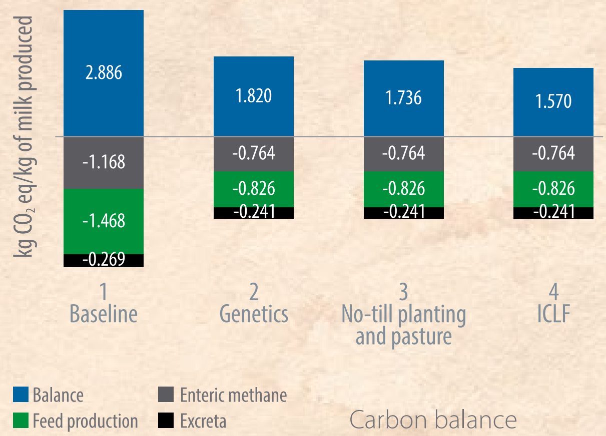
ZHOU, Y.; ZHAO, X.; LI, Y.; XU, J.; BI, A.; KANG, L.; XU, D.; CHEN, H.; WANG, Y.; WANG, Y.-G.; LIU, S.; JIAO, C.; LU, H.; WANG, J.; YIN, C.; JIAO, Y. LU, F. *Triticum* population sequencing provides insights into wheat adaptation. **Nature Genetics**, v. 52, p. 1412-1422, 2020. DOI: https://doi.org/10.1038/s41588-020-00722-w.

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.