sustainability

IMPACT FACTOR 3.3

CITESCORE 7.7

Article

State-Level Inventories and Life Cycle GHG Emissions of Corn, Soybean, and Sugarcane Produced in Brazil

Lucas G. Pereira, Nilza Patrícia Ramos, Anna Leticia M. T. Pighinelli, Renan M. L. Novaes, Joaquim E. A. Seabra, Henrique Debiasi, Marcelo H. Hirakuri and Marília I. S. Folegatti

MDPI

https://doi.org/10.3390/su17188482

sustainability

MDPI

Article

State-Level Inventories and Life Cycle GHG Emissions of Corn, Soybean, and Sugarcane Produced in Brazil

Lucas G. Pereira [1,*], Nilza Patrícia Ramos [1], Anna Leticia M. T. Pighinelli [1], Renan M. L. Novaes [1], Joaquim E. A. Seabra [2], Henrique Debiasi [3], Marcelo H. Hirakuri [3] and Marília I. S. Folegatti [1]

[1] Embrapa Environment, Rodovia SP340, km 127.5, Jaguariúna 13918-110, São Paulo, Brazil; nilza.ramos@embrapa.br (N.P.R.); anna.pighinelli@embrapa.br (A.L.M.T.P.); renan.novaes@embrapa.br (R.M.L.N.); marilia.folegatti@embrapa.br (M.I.S.F.)

[2] School of Mechanical Engineering, University of Campinas (UNICAMP), R. Mendeleyev, 200, Cidade Universitária, Campinas 13083-860, São Paulo, Brazil; jseabra@fem.unicamp.br

[3] Embrapa Soybean, Rodovia Carlos João Strass, s/nº Acesso Orlando Amaral, Distrito de Warta, Londrina 86001-970, Paraná, Brazil; henrique.debiasi@embrapa.br (H.D.); marcelo.hirakuri@embrapa.br (M.H.H.)

* Correspondence: lucgpereira@gmail.com

Abstract

Brazil is a leading producer of multi-purpose crops—such as corn, soybean, and sugarcane—used for human consumption, animal feed, and biofuel production. This study generated agricultural inventories for these three crops based on state-level information. For sugarcane, we used primary data submitted by ethanol producers to RenovaBio. For soybean and corn, we retrieved and updated data from a previous study, which gathered information through panel consultations with farmers and sector experts. We also calculated the greenhouse gas (GHG) emissions associated with the crops using the Life Cycle Assessment (LCA) method. Our analysis revealed significant variability in emissions across states, especially for corn and sugarcane. Without considering direct land use change (dLUC), the states with the highest and lowest emissions for each crop were as follows: (i) sugarcane: Paraíba at 54 and Goiás at 37, with a national average of 42 kg CO_2e/t cane; (ii) soybean: Maranhão at 344 and Minas Gerais at 300, average of 323 kg CO_2e/t soy; (iii) first-crop corn: Maranhão at 416 and Mato Grosso at 264, average of 300 kg CO_2e/t corn; (iv) second-crop corn: Paraná at 306 and Minas Gerais at 153, average of 255 kg CO_2e/t corn. Emissions were inversely related to crop yields, with the exception of second-crop corn. In general, lower yields were observed in states of the Northeast region (e.g., Maranhão and Paraíba), which face challenges due to irregular climate patterns and water deficits. For sugarcane cultivated in the same region, emissions from straw burning had a significant impact, with the practice being applied to more than 60% of the crop area. If dLUC emissions were included, variability would increase dramatically—particularly for corn and soybean in some states—due to patterns of cropland expansion into native vegetation areas over the 2000–2019 period. In particular, total soybean emissions would range from 471 in Paraná to 2173 in Maranhão, with a national average of 1022 kg CO_2e/t soy. These findings can be valuable as references for life cycle databases, for the development of state-specific emission factors for biofuels produced from the investigated crops, and as supporting information for decarbonization programs.

Keywords: LCA; GHG emissions; sugarcane; soybean; corn

Academic Editor: Georgios Koubouris

Received: 6 August 2025
Revised: 14 September 2025
Accepted: 17 September 2025
Published: 22 September 2025

Citation: Pereira, L.G.; Ramos, N.P.; Pighinelli, A.L.M.T.; Novaes, R.M.L.; Seabra, J.E.A.; Debiasi, H.; Hirakuri, M.H.; Folegatti, M.I.S. State-Level Inventories and Life Cycle GHG Emissions of Corn, Soybean, and Sugarcane Produced in Brazil. *Sustainability* **2025**, *17*, 8482. https://doi.org/10.3390/su17188482

1. Introduction

Brazil is a leading global producer of multi-purpose crops—such as corn, soybean, and sugarcane—used for human consumption, animal feed, and biofuel production. In 2023, the country ranked as the top producer of soybean (152 million metric tons, Mt soy) and sugarcane (783 Mt cane) and the third-largest producer of corn (132 Mt corn), trailing only the US and China [1]. Together, these three crops occupied over 75 million hectares, accounting for 80% of the country's harvested area [2,3]. Brazil was also the second-largest producer of ethanol (35.6 billion liters) and biodiesel (7.5 billion liters) in 2023, contributing 30% and 15% of the global output, respectively [4–6]. While sugarcane has long been the primary feedstock for ethanol production, corn's share has grown significantly, rising from less than 3% in 2018 to over 16% in 2023, equating to nearly 6 billion liters [7,8]. Similarly, soybean is essential for the production of biodiesel, with its oil representing 70% of the feedstock used in 2023 [4]. These crops play a vital role not only in the country's economy, but also in advancing low-carbon strategies. In this sense, to assess their contributions—especially to the supply of food and raw materials for bioenergy—it is important to determine the environmental impacts associated with their production systems.

Life cycle assessment (LCA) [9,10] is a tool that is widely used to calculate these impacts by examining inputs and emissions throughout the various stages of the supply chain. In LCA, life cycle inventories are considered the most important component [11–13], in which data on material and energy use at different stages are compiled. Ideally, inventories should be prepared based on primary data, but it is common for LCA studies to rely on data provided at aggregate levels (e.g., country or trading bloc) that represent average technological and environmental conditions [14–16]. As LCA has been applied to a variety of products—especially agricultural commodities, which are characterized by significant variations—there has been an increasing demand for spatially differentiated and temporally specific data in the construction of inventories [17]. Environmental policies and programs that rely exclusively on national-level information do not consider the significant geographical heterogeneity of crop production systems, as is the case in Brazil. With agricultural lands and biofuel production units dispersed across states and regions, characterized by diverse climates, soils, and management practices, national averages fail to adequately represent the complexity of the country's agricultural landscape. Therefore, developing representative inventories that capture the variability in the impacts of these crop production systems, both at national and sub-national levels, is essential to support effective decarbonization strategies.

Efforts to characterize agricultural production systems in Brazil by generating inventories with representative data at sub-national levels include a project supported by the Sustainable Recycling Industry (SRI), in which Matsuura et al. [18] developed inventories for key Brazilian agribusiness products including sugarcane, soybean, corn, mango, eucalyptus, and beef. The data from this study were incorporated into the Ecoinvent database v3.6 [19], and the findings were published in a report by the Ecoinvent Association [20]. In a recent report series, Ramos et al. [21] studied the regionalization of typical profiles of corn, soybean, and sugarcane production in Brazil. Worldwide, efforts to regionalize agricultural inventories include GHGenius [22], an LCA model developed for transportation fuels that focuses primarily on the national level but offers sub-national data on crop yield and nitrogen (N) fertilizer use for regions in the US and Canada. For corn production, Pelton [23] compiled an inventory using data at the county level in the US, finding that GHG emissions can vary as much as 300% across regions (Northeast versus Midwest). In a study to determine the geographic variability of agriculture, Yan et al. [24] compiled state-specific inventories for four major crops in the US (i.e., corn, cotton, soybean, and wheat).

Recently, the importance of agricultural inventories has extended beyond academic research, as national and international low-carbon fuel standards and regulatory schemes have adopted them for the calculation of biofuel impacts, with consequences for investments and policy decision-making [25]. Examples include their use in assessing sustainable aviation fuels (SAFs) for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) by the International Civil Aviation Organization [26] and low-carbon marine fuels (GHG Strategy and Net Zero Framework) under the International Maritime Organization [27]. In addition, innovative platforms such as Hestia [28] and Trase [29] leverage sub-national agricultural inventories to evaluate the sustainability of farms and food products across different countries, providing relevant information for trade discussions.

This study had two main objectives. First, we compiled representative agricultural inventories of the three major crops cultivated in Brazil (i.e., corn, soybean, and sugarcane) at the state level. The inventories were built primarily using data provided by farmers and biofuel producers from the various states of the country, with supplementary information retrieved from statistical reports and the scientific literature. Second, we used the inventories to calculate the GHG emissions associated with the production systems of these crops. The results can be valuable as references for feeding life cycle inventory (LCI) databases and developing state-specific emission factors for biofuels in Brazil produced from the investigated crops for use in international low-carbon schemes. To the best of our knowledge, this is the first effort in a single study to obtain representative inventories using primary data and GHG emissions at the state level in Brazil for the three main crops produced in this country.

2. Materials and Methods

The methodological steps to generate the agricultural inventories and calculate the life cycle GHG emissions of the three crops investigated are presented in Figure 1. The approach adopted also includes updating and validating the data obtained, as well as comparisons with results from other sources. We describe each step in detail in the following sections.

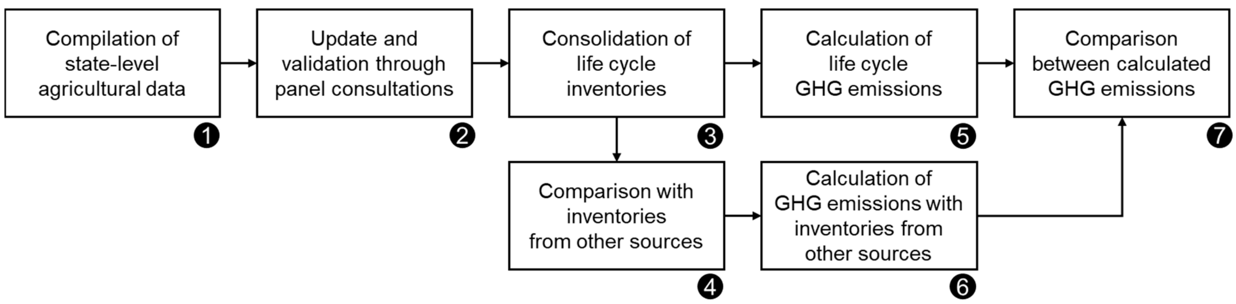

Figure 1. Flow diagram of the main methodological steps to generate the agricultural inventories and calculate the life cycle GHG emissions of the three crops (i.e., corn, soybean, and sugarcane) investigated at the state level. Numbers in boxes refer to the sequence of the steps taken.

2.1. State-Level Agricultural Inventories

Our primary challenge was compiling data, whether sourced from the biofuel and agricultural sectors or extracted from existing databases. Data selection was guided by the IPCC's quality criteria—transparency, completeness, consistency, comparability, and accuracy—detailed in Volume 1, Chapter 2: Approaches to Data Collection [30]. Table 1 summarizes the key sources of information used to generate the agricultural inventories of the three crops investigated. Given the specific characteristics and data availability for each crop production system, we detail the distinct aspects of the approaches in Sections 2.1.1 and 2.1.2. See Figure S1 (Supporting Information) for maps of Brazil, displaying state boundaries along with the average participation and yield of the harvested areas for the three crops, based on official statistical reports [2,3].

Table 1. Sources of information used to generate the agricultural inventories for the three crops investigated.

Sources	Corn	Soybean	Sugarcane
Yield	Average from Conab [3] and IBGE [2]	Average from Conab [3] and IBGE [2]	Conab [3], considering the total area [a]
Agricultural practices	Surveys from Hirakuri et al. [31]	Surveys from Hirakuri et al. [31]	Data submitted by producers to RenovaBio [32–34]
Direct land use change	BRLUC v2.0 [35,36]		
Reference period	2017–2019	2017–2019	2019–2021
Sample	0.4 Mha (1st crop) 3.5 Mha (2nd crop)	11.1 Mha	90 mills 187.4 Mt cane (27.4% of total)
States with raw data [b]	14 (7 considered representative for 1st crop and 8 for 2nd crop) (73.0%—1st crop) (96.4%—2nd crop)	14 (10 considered representative) (93.3%)	10 (7 considered representative) (86.7%)
Companies, institutions, and unions that took part in the validation process	Agronomic Institute of Campinas (IAC), CEOX Consulting, Embrapa Corn and Sorghum, FS, Inpasa Brasil, National Corn Ethanol Union (UNEM), National Union of Bioenergy (UDOP), Pecege Institute	3tentos, Bayer, Biofuels Producers Association of Brazil (APROBIO), Brazilian Association of Vegetable Oils Industry (Abiove), Brazilian Biodiesel and Bioquerosene Union (Ubrabio), Bunge, Embrapa Soybean, Federal University of Mato Grosso (UFMT), University of Rio Verde (UniRV)	Agronomic Institute of Campinas (IAC), Brazilian Biorenewables National Laboratory (LNBR), Embrapa Cerrados, ENER Consult, National Union of Bioenergy (UDOP), Organization of Sugarcane Producers Associations of Brazil (ORPLANA), Raízen, São Paulo State University (Unesp), Union of Sugarcane and Bioenergy Industry (UNICA)

[a] Total area includes harvested and unproductive seedling and planting areas; [b] Brazil has 27 states, and values in brackets refer to the percentage of production participation of the states considered representative in this study.

We validated the inventories generated during meetings with researchers, representatives of private companies, and associations of biofuel producers. As a final step to verify and refine detailed information, we consulted with experts in agricultural management practices for the three crops investigated. For corn and soybean, we held two meetings with 92 participants while, for sugarcane, we held three meetings with 85 participants. Section 3.1.1 presents the modifications in the values obtained from the ProspecSoy project for corn and soybean and in the information submitted to RenovaBio by sugarcane ethanol producers, as well as the assumptions adopted based on the recommendations from the meetings and consultations.

2.1.1. Sugarcane Inventory

For sugarcane, we obtained information from data submitted by biofuel producers to Brazil's National Biofuel Policy (RenovaBio) [32–34]. As of August 2024, RenovaBio has certified 329 biofuel plants, including 273 sugarcane ethanol plants [37]. The significant number of certified sugarcane processing units provided high-quality primary data on the agricultural production stage, ensuring robust representation of key characteristics across states. We focused on the period from 2019 to 2021. Although the certification process began in 2018, data from that year were limited. Similarly, while data for 2022 were available, they accounted for only 7% of the production certified in 2021. Therefore, data from 2018 and 2022 were excluded from our analysis.

To construct the inventories, we selected states with an average contribution of over 0.7% to domestic sugarcane production during the 2019–2021 period [2,3]. Collectively, the remaining states accounted for only 2.7% of total production during this timeframe. Detailed sugarcane data for all 27 Brazilian states are provided in Tables S1 and S2 (Supporting Information).

Primary data from each certified processing unit located within the selected states were retrieved for the analysis period. Our team filtered the information to exclude penalized values (i.e., optional values provided by the program in case the data are unknown or unavailable) reported by farmers and included only actual primary data. To ensure data quality, we identified and addressed abnormal values such as outliers, errors in decimal separators, and duplicate entries.

Table S3 (Supporting Information) presents the production of certified mills compared with the production of the total sugarcane area across the states. It also includes the number of certified mills per state, as well as those that provide primary data. On average, 27% of Brazil's sugarcane production was certified between 2019 and 2021. Mills certified by RenovaBio do not report data on sugarcane yield. According to Conab [3], the yield values for total sugarcane areas are, on average, 15% lower than those for harvested areas. This difference arises because the yield for total areas accounts for various land uses associated with the crop, including both harvested and unproductive areas, such as those used for planting and seedlings.

2.1.2. Soybean and Corn Inventories

For corn and soybean, we could not use information submitted by producers to RenovaBio. While 37 biodiesel plants were certified under the program, only 6 primarily used soybean oil as the feedstock for biofuel production. Similarly, just 8 out of 29 corn ethanol plants had been certified as of August 2024 [37]. In addition to the limited number of certified plants, no soybean biodiesel mills provided primary data, nor did most corn ethanol mills.

As an alternative, we sourced data at the sub-national level for Brazil from the literature, statistical institutes, and life cycle databases such as Ecoinvent v3.9.1 [38] and the Global Feed LCA Institute [39]. These databases contained the most comprehensive inventories for soybean and corn, largely based on data from the ProspecSoy project conducted by Embrapa Soybean [31]. The project characterized predominant production systems in key soybean-producing regions of Brazil for the 2017, 2018, and 2019 harvests. It involved 53 panel meetings across major soybean-producing microregions and municipalities. These structured consultations included hundreds of participants such as farmers, technical consultants, rural extension agents, members of producers' associations, agronomists from agricultural cooperatives, rural union representatives, financial agents, input retailers, and health agency members. Although the project focused primarily on soybean, the complementary nature of corn production enabled the collection of primary data for both crops. By extrapolating microregion-level data, the study characterized production systems for soybean and corn in various states, detailing agricultural inputs (fertilizers, pesticides, and soil amendments), mechanical operations, and yields. Table S4 (Supporting Information) presents parameters for soybean production across different states, accounting for the dedicated area based on official statistics and regions studied in the ProspecSoy project. Further details on the microregions considered for both soybean and corn are available in Tables S7 and S11 (Supporting Information), respectively.

The inventories for soybean production in the states of Bahia, Goiás, Maranhão, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Piauí, Paraná, Rio Grande do Sul, São Paulo, and Tocantins were sourced from Ecoinvent v3.9.1 [38], with updates detailed in Section 3.

The corn production system in Brazil differs from that of most other crops, in that it consists of two harvests within a 12-month period [40]. The first crop, a traditional harvest, is sown during the spring–summer (rainy season), typically between September and December in most of Brazil. The second crop, known as "safrinha," has emerged more recently, with planting mainly occurring after soybean harvests between January and March. In recent years, the area allocated to first-crop corn has decreased, offset by a rise in the yield and area dedicated to second-crop corn [41]. Parameters for both corn crops in different Brazilian states are provided in Table S8 (Supporting Information), based on official statistics and the regions studied in the ProspecSoy project. This dual harvest system is crucial for understanding the variations in agricultural inputs, operations, dedicated areas, and yields, which are influenced by the timing of the harvest in each state.

2.2. National Agricultural Inventories

To estimate the national inventory for each crop, we applied weighted averages, considering the participation of states in the production. In the crop inventories, we indicate the value used in the category "Participation to generate the national inventory," which only considers the participation between states for which primary data were available and that we considered representative. This assumption slightly increased the states' individual participation compared with the "Participation in the national production" category (Tables S13–S16 (Supporting Information)).

For sugarcane, we did not consider states for which no more than two mills provided primary data (i.e., Bahia, Mato Grosso, Paraná, and Pernambuco). These states represent 12% of the total national production combined (Table S13 (Supporting Information)). For corn and soybean, only states listed in the ProspecSoy project were considered, and no assumptions regarding proxies for similar states were made. Using the information provided in this study, other methods to compose the national inventory can be applied in future research to estimate the national inventories, such as including states based on similarity (e.g., location, climate, agricultural practices) with states considered representative.

2.3. Calculation of Life Cycle GHG Emissions

We primarily used Ecoinvent v3.9.1 [38] to obtain the life cycle emissions of the GHGs (fossil carbon dioxide (CO_2), fossil and biogenic methane (CH_4), and dinitrogen monoxide (N_2O)) associated with the production (background processes) of the agricultural inputs, energy, and fuels listed in the inventories of all three crops. The characterization factors used to convert CH_4 and N_2O into CO_2e (carbon dioxide equivalent) (in kg GHG/kg CO_2e) were based on the Sixth Assessment Report (AR6) of the IPCC (fossil CH_4 = 29.8, biogenic CH_4 = 27.2, and N_2O = 273.0) [42].

Table S12 (Supporting Information) presents the life cycle greenhouse gas (GHG) emissions (in g CO_2e) associated with the production of selected items. In addition to the background processes of limestone, urea, and fuels, we also considered emissions that occur after their use in the field. For the first two, emissions after application in the field were based on the IPCC Guidelines for National Greenhouse Gas Inventories [43], as no updates were provided in the IPCC's 2019 document [30]. For the fuels, emissions from combustion in engines were calculated using values from RenovaBio's technical report [44]. For sugarcane production, where applicable, we included N_2O and biogenic CH_4 emissions from straw burning, using values from the GREET model [45].

Another key category of emissions considered in our study is the direct and indirect N_2O emissions associated with nitrogen (N) application from synthetic and organic fertilizers in the soil, as well as nitrogen fixation in crop residues. Direct emissions arise when an increase in available nitrogen enhances nitrification and denitrification rates, while indirect N_2O emissions result from off-site nitrogen volatilization and leaching. For these calculations, we used the emission factors for each crop as outlined in the IPCC guidelines (Volume 4, Chapter 11: N_2O emissions from managed soils and CO_2 emissions from lime and urea application) [30]. See the Calculation of direct and indirect N_2O emissions section of the Supporting Information for factors and parameters used for the three crops.

We added a level of uncertainty to the emission factors of the selected inputs/outputs, assigning triangular distributions of probabilities (i.e., minimum, most likely, and maximum values), applied using the @Risk software v7.5 [46] (Table 2). For most likely values, we considered the emissions from Ecoinvent v3.9.1 [38], whereas for minimum and maximum values, we examined two other relevant sources of GHG emission factors: database v13520 from the GREET model [47], which has been mostly developed focusing on industrial inputs and processes representative to the US, and a list from ISCC EU 205 [48], which is based on Ecoinvent v3.7 [49], the JEC E3-Database 2008 [50], and other EU databases. In some cases, the most likely value was also considered the minimum or maximum value.

Table 2. Range of values assigned to the life cycle GHG emissions of selected inputs/outputs considered in the agricultural stages of sugarcane, soybean, and corn production.

Inputs/Outputs	Unit	Minimum	Most Likely	Maximum
Production				
Limestone (calcitic/dolomitic)	g CO_2e/kg	10.5	38.8	130.0
Urea	g CO_2e/kg N	1179.8	3487.4	3487.4
Monoammonium phosphate (MAP)	g CO_2e/kg P_2O_5	1011.0	1946.2	1946.2
Potassium chloride	g CO_2e/kg K_2O	576.0	626.2	626.2
Corn seeds	g CO_2e/kg	1250.2	1250.2	1979.4
Soybean seeds	g CO_2e/kg	400.0	431.8	2.808.8
Diesel	g CO_2e/kg	562.7	668.5	668.5
Emissions from use				
Limestone (dolomitic)	g CO_2e/kg	220.0	480.0	480.0
Limestone (calcitic)	g CO_2e/kg	220.0	440.0	440.0
Urea	g CO_2e/kg N	620.0	1560.0	1560.0
Diesel	g CO_2e/kg	3156.6	3156.6	3222.5

In addition, we examined the state-level direct land use change (dLUC) associated with the agricultural production of the crops studied, using the open-access tool Brazilian Land Use Change (BRLUC v2.0) [36], developed by Garofalo et al. [35]. This tool estimates the CO_2 balance for a wide range of agricultural products in Brazil at the municipal, state, and national levels using spatially explicit land conversion data with a 30 m resolution. The estimates are based on the stock–differences method, in line with IPCC guidelines [30]. For dLUC, we used 2019 as the reference year, which is within the inventory period of the three crops evaluated. We used a 20-year looking-back period (2000–2019) and those same 20 years as the amortization period, which is the recommendation in most LCA standards on carbon footprints [51].

2.4. Comparison with Inventories and GHG Emissions Reported in the Literature

We compared the inventories compiled in our study with data from the national and state-level inventories of the three crops investigated, using relevant commercial and independent sources: The Resolution 758 [34], GHGenius [22], and BioGrace [52] models; the Agri-footprint v6.3 [53] and Ecoinvent v3.9.1 [38] databases; and a study on GHG emissions from soybean production in Brazil [54]. Agri-footrint and Ecoinvent are largely used in studies on the environmental impacts of food products and biofuels, especially within international low-carbon fuel standards and regulatory schemes.

Additionally, we used these inventories to calculate the life cycle GHG emissions for comparison with the results of this study. Notably, we excluded emissions from dLUC in this comparison and did not account for emissions related to land transformation and infrastructure in the other sources for the purpose of this analysis.

We calculated the emissions using SimaPro v9.6.0.1 [55] and the IPCC 2021 GWP100 v1.02 method [42] for the inventories from the commercial databases (i.e., Agri-footprint v6.3 and Ecoinvent v.3.9.1). For inventories from the Resolution 758 document and the GHGenius and BioGrace models, we applied the method described in Section 2.3. The impact value for soybean production in Mato Grosso, as calculated by Cerri et al. [54], was retrieved directly.

2.5. Caveats and Limitations

Primary data

RenovaBio is a relatively new low-carbon fuel program, and most biofuel plants do not yet provide primary data. As of August 2024, 329 biofuel plants were certified, which represents over 90% of all operating plants in Brazil [37], but we could only obtain primary data from 90 sugarcane mills from previous years (Table S3 (Supporting Information)). As previously mentioned, biofuel producers have the option to use default (penalized) values, which are based on national averages, for the agricultural stage when filling out certification information. These cases were identified and filtered out from our analysis.

For some states (e.g., Bahia and Mato Grosso), only one mill provided primary data, although as many as 13 had been certified in the case of Mato Grosso. The states we did not consider representative were not included in the estimation of the national inventory, although their individual inventories are presented in Table S13 (Supporting Information) for transparency, indicating the number of certified mills that provide primary data. The lack of a clear statement or indication as to whether the data provided were default or actual primary data in certified mills in RenovaBio can lead to the misuse of this information: in a recent study, Liu et al. [56] used data submitted by 67 mills to RenovaBio to evaluate the life cycle GHG emissions of sugarcane ethanol with the GREET model; however, unlike our study, they did not filter out agricultural profiles with penalized values, which potentially had a significant impact on the results. As for corn ethanol and soybean biodiesel, we did not identify a sufficient amount of reliable primary data from certified producers for inclusion in our study. Alternatively, for corn and soybean, we retrieved information from a previous project (i.e., ProspecSoy). We anticipate that, as the program matures and plant management systems improve, more comprehensive primary data will become available.

Reference years

The ProspecSoy project [31], used for corn and soybean, provided average values for the 2017–2019 period, different from the 2019–2021 period used for the sugarcane production analysis. We made an effort to ensure that the statistical data used [2,3] aligned with the same period as the data retrieved from RenovaBio and the project. However, it is noteworthy that emission factors for various processes, as compiled by life cycle databases (e.g., Ecoinvent), are typically based on average values from multiple reference years, depending on the availability, transparency, and quality of the data. Using data, parameters, and factors from various sources and reference years in the same analysis is a widely accepted practice within the LCA community.

Land use change

This study adopted an attributional approach to assess the life cycle inventory of GHG emissions (carbon footprint), aligned with the general recommendations in ISO 14067 [57]. Therefore, although indirect effects and other socioeconomic aspects associated with LUC are relevant aspects of the overall sustainability of agricultural production [58,59], they are beyond the scope of this study and the mandatory items under ISO 14067 [57]. In addition, for dLUC, we used inventory and amortization periods of 20 years. Although other periods can be used and affect results, the 20-year period is the most commonly used by carbon footprint standards [51]. Increasing amortization periods (e.g., from 20 to 25 years), while maintaining the inventory period of 20 years (2000–2019), would decrease dLUC emissions. Conversely, reducing the amortization period would increase dLUC. However, the consistency of using different periods remains to be investigated. Changing the inventory time—for example, looking back 10 instead of 20 years—can have variable effects depending on the crop, time, and geographical scope [51].

3. Results and Discussion

3.1. Agricultural Inventories

3.1.1. Obtained in This Study

Tables 3–6 present the inventories for corn, soybean, and sugarcane for the top five producing states of each crop produced in Brazil. See Tables S13–S16 (Supporting Information) for detailed inventories of all producing states. A key feature of our study is the use of specified items. For limestone, we were able to distinguish between dolomitic and calcitic varieties. For fertilizers (N and P_2O_5), we gathered data on various types, namely, ammonium nitrate, ammonium sulfate, anhydrous ammonia, calcium ammonium nitrate (CAN), diammonium phosphate (DAP), monoammonium phosphate (MAP), and urea ammonium nitrate (UAN). This level of detail is also reflected in the inventory for sugarcane, where we specified different types of fuels used in agricultural operations (e.g., biodiesel, gasoline, and ethanol) and electricity sources. This distinction enabled us to align each item with its precise corresponding life cycle emission factor, providing valuable and detailed information.

Sugarcane

For the sugarcane inventory, we adjusted the values of N and P_2O_5 in MAP and DAP to align the concentrations with the N content. In cases where these adjustments resulted in an increase in the amount of P_2O_5, we classified the excess under the category "Other synthetic P_2O_5 fertilizers." A limitation of the data retrieved from RenovaBio on sugarcane is the inability to differentiate between types of pesticides, as the quantities per area are fixed, as defined in RenovaBio's technical report [44]. The percentage of burned area, a critical factor influencing GHG emissions from sugarcane, ranges from 2 to 5% in states with significant contributions to national production (e.g., Goiás, Minas Gerais, Mato Grosso do Sul, Paraná, and São Paulo). By contrast, northeastern states with smaller shares of national production (e.g., Alagoas, Bahia, Paraíba, and Pernambuco) still rely heavily on burning, with rates ranging from 52 to 86%. Based on the weighted average of the states, we estimate the overall burning percentage for Brazil to be 7.3%, which is lower than the 18% average indicated for the country in Resolution 758 [34].

Table 3. Inventory of sugarcane production in Brazil for selected states (2019–2021) (see Table S13 (Supporting Information) for the complete state and national inventories).

Data	Unit	São Paulo	Goiás	Minas Gerais	Mato Grosso do Sul	Brazil [i]
Certified mills with primary data	n.	33	18	17	7	90
Participation used to generate the national inventory [a]	%	54.9%	10.9%	10.4%	7.0%	-
Yield [b]	t cane/ha	65.86	65.29	68.52	61.28	58.27
Burned area	%	4.84	4.20	5.29	1.80	7.31
Direct land use change (dLUC) [c]	t CO_2e/ha.yr	0.40	−0.21	0.16	0.40	0.28
Limestone [d]	kg/t cane	11.87	8.93	13.03	14.96	11.85
Gypsum	kg/t cane	5.37	3.63	6.09	4.36	5.01
Synthetic N fertilizers [e]	kg N/t cane	1.00	0.90	1.00	1.15	1.01
Synthetic P_2O_5 fertilizers [f]	kg P_2O_5/t cane	0.60	0.57	0.69	0.86	0.62
Synthetic K_2O fertilizers [g]	kg K_2O/t cane	0.78	0.84	0.94	0.86	0.84
Diesel [h]	L/t cane	4.23	3.93	4.33	4.01	4.12
Grid electricity	kWh/t cane	0.04	0.57	0.14	-	0.91

[a] Using average values from official statistics for the 2017–2019 period [2,3], distributed between representative states only; [b] Yield based on the average hectare (considers the total land associated with the crop, which includes unproductive areas used for planting, seedling, and harvesting) [3]; [c] From Brazilian Land Use Change (BRLUC v2.0) [35,36]: average emissions from direct land use change (dLUC) of sugarcane (2000–2019); [d] Dolomitic and calcitic limestone. [e] Ammonium nitrate, ammonium sulfate, anhydrous ammonia, calcium nitrate, diammonium phosphate (DAP), monoammonium phosphate (MAP), urea ammonium nitrate (UAN), urea, and other unspecified synthetic N fertilizers; [f] Diammonium phosphate (DAP), monoammonium phosphate (MAP), single superphosphate (SSP), triple superphosphate (TSP), and unspecified synthetic P_2O_5 fertilizers; [g] Potassium chloride and unspecified synthetic K_2O fertilizers; [h] Fossil diesel mixed with biodiesel (10%, 11%, 12% *v*/*v*); [i] Weighted average, based on the production participation of representative states.

Table 4. Inventory of soybean production in Brazil for selected states (2017–2019) (see Table S15 for the complete inventory, including all specified items and producing states).

Data	Unit	Mato Grosso	Paraná	Rio Grande do Sul	Goiás	Mato Grosso do Sul	Brazil [h]
Participation used to generate the national inventory [a]	%	29.5%	16.9%	15.6%	10.7%	8.8%	-
Yield [b]	t soy/ha	3.36	3.65	2.98	3.38	3.42	3.34
Direct land use change (dLUC) [c]	t CO_2e/ha.yr	3.40	0.59	2.03	0.87	0.70	2.32
Limestone [d]	kg/t soy	148.98	136.93	167.68	147.97	146.04	149.80
Gypsum	kg/t soy	-	-	-	16.01	39.78	5.67
Seeds	kg/t soy	14.72	12.32	16.10	16.93	12.18	14.52
Synthetic N fertilizers [e]	kg N/t soy	5.75	4.90	3.92	3.64	4.47	4.74
Synthetic P_2O_5 fertilizers [f]	kg P_2O_5/t soy	32.27	27.96	22.60	28.32	24.74	28.26
Potassium chloride	kg K_2O/t soy	22.35	19.20	29.81	21.54	21.67	22.85
Diesel [g]	L/t soy	10.52	11.17	13.18	10.92	12.06	11.23
2,4-D	kg/t soy	0.04	0.21	0.05	0.14	0.34	0.12
Glyphosate	kg/t soy	0.99	0.79	0.97	0.89	1.18	1.00
Pesticides	kg/t soy	0.61	0.63	1.73	0.86	0.77	0.91

[a] Using average values from official statistics for the 2017–2019 period [2,3], distributed between representative states only; [b] Estimated from the ProspecSoy project for the 2017–2019 period [31]. See Table S7 (Supporting Information) for information on the yields of the microregions used to estimate the values for states; [c] From Brazilian Land Use Change (BRLUC v2.0) [35,36]: average emissions from direct land use change (dLUC) of soybean (2000–2019); [d] Dolomitic limestone; [e] Ammonium sulfate, monoammonium phosphate (MAP), and urea; [f] Monoammonium phosphate (MAP), single superphosphate (SSP), and triple superphosphate (TSP); [g] Fossil diesel mixed with biodiesel (10% *v*/*v*); [h] Weighted average, based on the production participation of representative states.

Table 5. Inventory of first crop corn production in Brazil for selected states (2017–2019) (see Table S15 for the complete inventory, including all specified items and producing states).

Data	Unit	Rio Grande do Sul	Minas Gerais	Paraná	Goiás	Bahia	Brazil [h]
Participation used to generate the national inventory [a]	%	26.2%	24.3%	17.5%	9.3%	8.6%	-
Yield [b]	t corn/ha	7.26	9.00	10.56	8.40	6.60	7.26
Direct land use change (dLUC) [c]	t CO_2e/ha.yr	1.95	1.62	1.33	1.33	1.98	2.01
Limestone [d]	kg/t corn	68.87	55.56	47.36	59.52	75.76	61.76
Gypsum	kg/t corn	-	-	-	2.71	-	0.25
Seeds	kg/t corn	2.75	2.22	1.89	2.38	3.03	2.47
Synthetic N fertilizers [e]	kg N/t corn	15.36	18.47	17.88	18.93	23.86	18.23
Synthetic P_2O_5 fertilizers [f]	kg P_2O_5/t corn	16.50	13.34	6.84	10.71	18.18	13.57
Potassium chloride	kg K_2O/t corn	11.02	17.33	11.37	4.29	12.12	13.66
Diesel B10 [g]	L/t corn	5.70	4.70	3.76	5.25	4.68	4.82
2,4-D	kg/t corn	-	-	0.05	0.05	0.05	0.02
Glyphosate	kg/t corn	0.17	0.17	0.12	0.21	0.25	0.19
Pesticides	kg/t corn	0.69	0.78	0.80	0.79	1.02	0.76

[a] Using average values from official statistics for the 2017–2019 period [2,3], distributed between representative states only; [b] Estimated from the ProspecSoy project for the 2017–2019 period [31]. See Table S11 (Supporting Information) for information on the yields of the microregions used to estimate the values for states; [c] From Brazilian Land Use Change (BRLUC v2.0) [35,36]: average emissions from direct land use change (dLUC) of corn (2000–2019); [d] Dolomitic limestone; [e] Ammonium sulfate, monoammonium phosphate (MAP), and urea; [f] Monoammonium phosphate (MAP), single superphosphate (SSP), and triple superphosphate (TSP); [g] Fossil diesel mixed with biodiesel (10% *v*/*v*); [h] Weighted average, based on the production participation of representative states.

Table 6. Inventory of second crop corn production in Brazil for selected states (2017–2019) (see Table S16 for the complete inventory, including all specified items and producing states).

Data	Unit	Mato Grosso	Paraná	Goiás	Mato Grosso do Sul	Minas Gerais	Brazil [h]
Participation used to generate the national inventory [a]	%	46.0%	18.0%	13.5%	13.2%	3.7%	-
Yield [b]	t corn/ha	6.30	6.26	6.18	5.24	5.50	6.06
Direct land use change (dLUC) [c]	t CO_2e/ha.yr	4.77	1.33	1.33	1.08	1.62	2.01
Limestone [d]	kg/t corn	80.90	80.90	80.90	80.90	80.90	79.61
Gypsum	kg/t corn	-	-	1.91	14.96	-	2.23
Seeds	kg/t corn	3.24	3.24	3.24	3.24	0.96	3.14
Synthetic N fertilizers [e]	kg N/t corn	12.52	17.59	10.80	16.18	4.88	13.31
Synthetic P_2O_5 fertilizers [f]	kg P_2O_5/t corn	8.59	8.20	7.48	5.42	2.53	7.71
Potassium chloride	kg K_2O/t corn	8.06	9.64	11.10	5.70	2.03	8.20
Diesel B10 [g]	L/t corn	4.97	6.32	5.85	5.83	1.92	5.30
2,4-D	kg/t corn	-	-	-	-	-	0.00
Glyphosate	kg/t corn	0.23	0.15	0.24	0.22	0.18	0.21
Pesticides	kg/t corn	0.26	0.32	0.52	0.58	0.14	0.35

[a] Using average values from official statistics for the 2017–2019 period [2,3], distributed between representative states only; [b] Estimated from the ProspecSoy project for the 2017–2019 period [31]. See Table S11 (Supporting Information) for information on the yields of the microregions used to estimate the values for states; [c] From Brazilian Land Use Change (BRLUC v2.0) [35,36]: average emissions from direct land use change (dLUC) of corn (2000–2019); [d] Dolomitic limestone; [e] Ammonium sulfate, monoammonium phosphate (MAP), and urea; [f] Monoammonium phosphate (MAP), single superphosphate (SSP), and triple superphosphate (TSP); [g] Fossil diesel mixed with biodiesel (10% *v*/*v*); [h] Weighted average, based on the production participation of representative states.

Soybean and corn

In accordance with specialist recommendations, the primary updates to values obtained from the ProspecSoy project for the soybean and corn inventories [31] are outlined as follows:

Soybean

(1) Average limestone application was set at 500 kg/ha.yr, based on farmers' practice of applying 3000 kg/ha every three years or 4000 kg/ha every four years, averaging

1000 kg/ha per year, split by soybean and another commercial crop (a common practice in Brazil that allows agricultural inputs to be shared between crops). The value estimated is below the 754.2 kg/ha used as a reference in Resolution 758 [34].

(2) Synthetic N application, represented by MAP, changed from 3.7 to 8.0 kg N/ha in Rio Grande do Sul and from 27.0 to 20.0 kg N/ha in Maranhão. For Rio Grande do Sul, specialists indicated that the original values had been underestimated whereas, for Maranhão, they were overestimated. The maximum value reported for the MAP application is limited to 20.0 kg N/ha, which guarantees the fixation of biological nitrogen according to Embrapa Soybean [60].

(3) Glyphosate application changed from 6.0 to 2.9 kg/ha in Paraná.

Corn

(1) The second-crop yield in the state of São Paulo changed from 4500 to 5500 kg/ha.

(2) Average limestone application was set at 500 kg/ha.yr, based on farmers' practice of applying 3000 kg/ha every three years, averaging 1000 kg/ha per year, split by corn and another commercial crop, as previously mentioned for soybean. The value estimated is above the 262 kg/ha used as a reference in Resolution 758 [34].

(3) Synthetic N application, represented by urea, changed from 29.3 to 100.0 kg N/ha for the second crop in the state of Mato Grosso do Sul, considering an increase in investments, with the expectation of higher yields to meet the attractive ethanol market in the state.

(4) Potassium application, represented by potassium chloride, changed from 0 to 80.0 kg K_2O/ha for the first crop in the state of Bahia and from 36.0 to 80.0 kg K_2O/ha in Goiás.

(5) Pesticide application for the first crop changed from 2.8 to 6.7 kg/ha in the state of Bahia, 2.3 to 6.6 kg/ha in Goiás, and 2.8 to 6.9 kg/ha in Piauí.

(6) Glyphosate application changed from 3.4 to 1.5 kg/ha for the first crop in the state of Minas Gerais.

To generate the national inventories, we used weighted average values for the inputs based on each state's share of production for each crop. Therefore, the values presented are not meant to accurately represent the application of fertilizers, soil amendments, and energy use but, rather, to provide a composite of average values that reflect a national profile.

3.1.2. Comparison with Inventories from Other Sources

We compare selected parameters from various studies and databases in Table 7. Although not clearly specified, in our opinion, based on the crop yields, fertilizer use, and electricity source, the soybean and corn inventories within the GHGenius and BioGrace models do not represent the production systems in Brazil and were not included in the comparison.

Table 7. Comparison of agricultural inventories from various studies for selected parameters.

(a) Sugarcane								
				Brazil			São Paulo	
Parameters	Unit	Agri-footprint [a]	BioGrace [b]	GHGenius [c]	Res 758 [d]	This study [e]	Ecoinvent [f]	This study [e]
Yield	t cane/ha	73.80	68.70	73.70	-	58.27	71.94	65.86
Burned area	%	-	75.24	-	18.00	7.31	-	4.84
Limestone	kg/t cane	5.42	5.34	4.44	5.79	11.85	1.75	11.87
Synthetic N fertilizers	kg N/t cane	1.04	0.91	1.40	1.11	1.01	1.09	1.00
Synthetic P_2O_5 fertilizers	kg P_2O_5/t cane	0.38	0.41	0.61	0.44	0.62	0.37	0.60
Synthetic K_2O fertilizers	kg K_2O/t cane	1.07	1.08	1.21	1.35	0.84	1.22	0.78
Diesel [h]	L/t cane	1.86	0.74	3.66	3.18	4.17	X [g]	4.23

Table 7. *Cont.*

(b) Soybean

Parameters	Unit	Brazil				Mato Grosso		
		Agri-footprint [a]	BioGrace [b]	Res 758 [d]	This study [i]	Cerri et al. [j]	Ecoinvent [c]	This study [i]
Yield	t soy/ha	3.11	2.80	-	3.34	3.13	3.36	3.36
Limestone	kg/t soy	128.60	-	249.00	149.80	140.26	77.60	148.98
Synthetic N fertilizers	kg N/t soy	2.65	2.86	2.80	4.74	2.24	5.41	5.75
Synthetic P_2O_5 fertilizers	kg P_2O_5/t soy	26.66	23.59	27.20	28.26	24.92	35.24	32.27
Synthetic K_2O fertilizers	kg K_2O/t soy	26.00	22.16	32.70	22.85	26.52	26.40	22.35
Diesel [h]	L/t soy	26.17	20.93	10.70	11.23	8.63	9.83	10.52

(c) Corn

Parameters	Unit	Brazil			Rio Grande do Sul (1st Crop)		Mato Grosso (2nd Crop)	
		Agri-footprint [a]	Res 758 [d]	This study [i] (1st Crop)	Ecoinvent [c]	This study [i]	Ecoinvent [c]	This study [i]
Yield	t corn/ha	5.15	-	7.26	7.26	7.26	6.30	6.30
Limestone	kg N/t corn	77.67	42.30	61.76	-	68.87	35.00	80.90
Synthetic N fertilizers	kg N/t corn	12.76	12.60	18.23	15.78	15.36	12.55	12.52
Synthetic P_2O_5 fertilizers	kg P_2O_5/t corn	6.85	10.90	13.57	16.84	16.50	9.36	8.59
Synthetic K_2O fertilizers	kg K_2O/t corn	7.47	11.20	13.66	10.80	11.02	7.80	8.06
Diesel [h]	L/t corn	18.39	4.80	4.82	5.34	5.70	4.70	4.97

[a] Agri-footprint v6.3 [53]; [b] EU [52]; [c] (S&T)2 Consultants [22]; [d] ANP [34]; [e] Data obtained from sugarcane mills certified in RenovaBio; [f] Ecoinvent v3.9.1 [38]; [g] Not presented as a separate amount. Diesel use is represented by agricultural operation processes (e.g., fertilizing, furrowing, harvesting, loading, planting, transfer, and transport) given in different units (e.g., ha and t.km) defined in the database; [h] Fossil diesel mixed with biodiesel (10–12% *v*/*v*); [i] Data derived from the ProspecSoy project [31], with modifications; [j] Cerri et al. [54].

Sugarcane

Most differences in parameters can be attributed to the use of data derived from various sources and reference years. Our study relies on primary data recently submitted by producers to RenovaBio, while Agri-footprint v6.3 [53] uses FAOSTAT [1] and IFASTAT [61]. BioGrace [52] uses values from Macedo et al. [62]; GHGenius [22] uses average values from three studies [62–64]; Ecoinvent v3.9.1 [38] uses a report by IDEA [65] and a study by Cavalett et al. [66]; and Resolution 758 [34] uses average values reported by the sugarcane sector [44].

The yield found in our study is lower than the values used in other sources. As explained in Section 2.1.1, the yield values we used account for the total land associated with the crop, including unproductive areas. While most other cases typically use yields based on harvested areas, we believe our approach is more comprehensive as it covers the entire production cycle, including agricultural inputs and emissions from land where planting, seedling, and reforming occur—not just where sugarcane is harvested.

Another parameter that varies across the sources is the burned area, which is a technique used for manual harvesting. The GHGenius model allows users to specify the burned area, but no default value is provided. BioGrace relies on an outdated value derived from Macedo et al. [62], from over two decades ago, when manual harvesting was common on about 80% of sugarcane land. In contrast, our study, Ecoinvent, and Resolution 758 use values that are more recent.

At the national level, the limestone usage found in our study (11.85 kg/t cane) is significantly higher than that reported in other sources (4.44–5.79 kg/t cane). This difference likely reflects the increased use of limestone during the reforming period, suggesting that the quality of the land used for sugarcane may be declining over time, or that lower-quality areas have been more recently occupied. The value presented by Ecoinvent for the state of São Paulo (1.75 kg/t cane) is an outlier, while the values used by the BioGrace and GHGenius models are based on outdated references, as noted by Pereira et al. [67].

The GHGenius and BioGrace models do not specify the types of N and P_2O_5 fertilizers used, while our study, Resolution 758, and Agri-footprint provide various categories (e.g., urea, DAP, MAP, UAN, single superphosphate (SSP), and triple superphosphate (TSP)). This omission can significantly impact the calculation of life cycle GHG emissions for sugarcane, as the impacts associated with fertilizer manufacturing vary widely depending on their type. For instance, the impact of producing urea is 3.49 kg CO_2e/kg N, whereas the impact of producing CAN is much higher, at 9.85 kg CO_2e/kg N (Table S12 (Supporting Information)). More details on how fertilizer types influence emissions calculations are provided in Section 3.2.2.

Diesel use found in this study—which we believe more accurately reflects the actual diesel demand—is higher than values from other sources. Assessing the diesel use in agricultural operations has traditionally been challenging when collecting data to compile inventories. In the case of Ecoinvent for São Paulo, it was not possible to retrieve the exact value because diesel use is dependent on agricultural operation processes in the inventories (e.g., fertilizing, field leveling, furrowing, planting, loading, and transferring, given in ha; and transport, given in t.km).

Soybean and corn

The parameter values obtained in our study are very similar to those from Ecoinvent for soybean and corn at the state level (i.e., soybean in Mato Grosso and corn in Rio Grande do Sul and Mato Grosso). This similarity is due to both datasets being derived from the ProspecSoy project [31]. The only exception is limestone use, for which we updated the values based on expert recommendations, as detailed in Section 3.1.1. These updated values are also consistent with the study by Cerri et al. [54] for soybean in Mato Grosso.

At the national level, values that stand out for being significantly higher than the averages include the limestone use for soybean, according to Resolution 758, and the diesel use for soybean and corn, according to the Agri-footprint database. Limestone use for soybean, from Resolution 758, is defined as an average value derived from information from the biodiesel sector in Brazil [44]. The discrepant value is explained because at that point in the program, limestone was not assumed to be split between soybean and the other commercial crop, but solely allocated to soybean. The diesel used for soybean and corn, from Agri-footprint, is based on the "Energy model for crop cultivation," which estimates the fuel demands for on-field activities and irrigation [53].

Considering that RenovaBio provides default (penalized) values in the profiles of corn, soybean, and sugarcane (Resolution 758 [34], based on national averages [44], the agricultural inventories compiled in this study can be particularly useful in updating those values, considering more representative conditions. The state-level information obtained can enable differentiation between the profiles of crop-producing states, which could incentivize biofuel producers to demand accurate primary data from crop producers instead of opting for default values in the certification process. Calculation of emission factors for Brazilian biofuels in international regulatory schemes, such as CORSIA and IMO's GHG Strategy and Net Zero Framework, can also benefit from the state-specific agricultural inventories of the main feedstocks used to produce biofuels (i.e., corn and sugarcane for ethanol and soybean for biodiesel).

3.2. Life Cycle GHG Emissions

3.2.1. Using the Inventories Obtained in Our Study

Figure 2 illustrates the life cycle GHG emissions (median values) for each crop, broken down by state and emission category, with the participation of each state in the production and emissions from dLUC highlighted as a separate category. For detailed numerical results by category, refer to Tables S17–S20 (Supporting Information). For the total life cycle GHG emissions considering a 90% confidence interval (5th percentile, 25th percentile, median, 75th percentile, and 95th percentile), refer to Table S21 (Supporting Information).

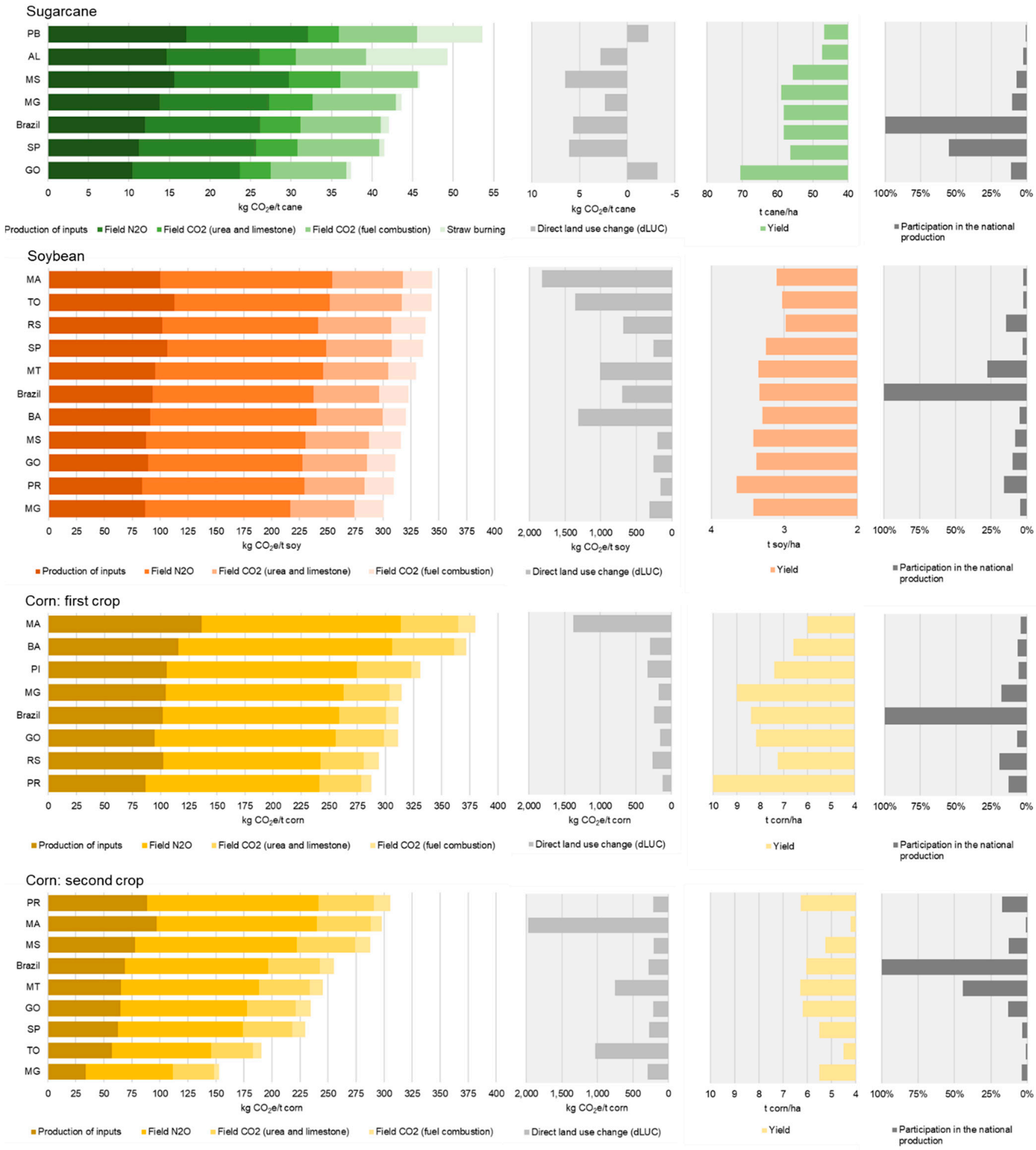

Figure 2. Life cycle GHG emissions of crop production by state and category (2019–2021 for sugarcane and 2017–2019 for soybean and corn), including direct land use change (dLUC) emissions (2019–2000) (all median values in kg CO_2e/t crop). In addition, the crop yields and the participation of each state in the total national production (in %) are shown. Note the different values on the horizontal axes for each crop. State abbreviations: Alagoas (AL), Bahia (BA), Goiás (GO), Maranhão (MA), Mato Grosso do Sul (MS), Mato Grosso (MT), Minas Gerais (MG), Paraíba (PB), Paraná (PR), Pernambuco (PE), Piauí (PI), Rio Grande do Sul (RS), São Paulo (SP), Tocantins (TO).

For sugarcane, we obtained a median value impact of 42.15 kg CO_2e/t cane for the country, excluding dLUC emissions, considering a weighted average based on the state-level inventories, as explained in Section 2.2. This value is close to that obtained for São Paulo, which holds 55% of the national sugarcane production. Goiás presented the most favorable results with the lowest impact at 37.42 kg CO_2e/t cane, whereas Paraíba was found to have the highest impact at 53.66 kg CO_2e/t cane. The main differences in life cycle GHG emissions between states were linked to agricultural input production (particularly fertilizers) and the straw-burning practice. In general, Northeastern states (e.g., Alagoas, Paraíba, and Pernambuco), where straw burning is still widespread and yields are lower due to climate conditions, tend to have higher emissions.

Tables 3 and S13 (Supporting Information) show that sugarcane production uses a total N fertilizer of 0.90 kg N/t cane in Goiás (0.34 of ammonium nitrate, 0.11 of ammonium sulfate, 0.0002 of CAN, 0.09 of MAP, 0.25 of urea, and 0.11 of other N), compared with 1.12 kg N/t cane in Paraíba (0.30 of ammonium nitrate, 0.25 of ammonium sulfate, 0.02 of DAP, 0.06 of MAP, 0.06 of urea, and 0.43 of other N fertilizer). The fact that Paraíba uses much more other (unspecified) synthetic N fertilizer (0.43 kg N/t cane) than Goiás (0.11 kg N/t cane) partly explains the difference in total emissions. The manufacturing impact of calcium nitrate (18.11 kg CO_2e/kg N) used as the proxy for unspecified N fertilizer, as recommended in RenovaBio's technical note [44], is the highest among all N fertilizers. As mentioned previously, another source of variability is the impact of straw burning. A considerable difference can be observed between the burned areas in Goiás (4.2%) and Bahia (52.1%). Those practices translate into 0.54 in Goiás versus 8.06 kg CO_2e/t cane in Paraíba. Across all states, emissions from the production of agricultural inputs varied between 10.38 and 17.09, while straw burning varied between 0.54 (Goiás) and 10.03 kg CO_2e/t cane (Alagoas).

When dLUC emissions were included, they significantly altered the results and became the primary source of variation among the states. At the national level, emissions increase by 13%, rising to 47.70 kg CO_2e/t cane, while state-level emissions range from 34.15 in Goiás to 53.60 kg CO_2e/t cane in Paraíba. Two states, Goiás and Paraíba, experience negative dLUC emissions, as sugarcane expansion occurs on agricultural lands with lower carbon stocks. In fact, a recent study, in which dLUC parameters were refined, found that sugarcane cultivation led to CO_2 net removals in central–southern Brazil between 2000 and 2020 [68]; therefore, future updates of our study should consider incorporating these results.

We observed a similar pattern for soybean, with the highest variations also found in the agricultural inputs category, where emissions ranged from 84.03 to 112.86 kg CO_2e/t soy. The percentage difference between the highest and lowest emissions across states was 14%, without accounting for dLUC (Maranhão at 343.83 and Minas Gerais at 300.41 kg CO_2e/t soy). When dLUC emissions were included, the results changed significantly, increasing emissions at the country level by 215% to 1021.09 kg CO_2e/t soy. State-level emissions saw a notable rise, particularly in states with more recent area expansion, including over natural vegetation, such as Maranhão, Tocantins, and Bahia. The emission differences among states became much more pronounced, with emissions in Maranhão being more than four times higher than in Paraná. Escobar et al. [69] reported comparable results on the impacts of soybean production in Brazil. Their study detected extremely large spatial variability in GHG emissions and found that the largest impacts were associated with municipalities across Maranhão, Tocantins, Piauí and Bahia (MATOPIBA states) and Pará, where soybean is directly linked to natural vegetation loss.

For corn, we observed significant variation across states not only in agricultural inputs but also in other categories, such as field N_2O and field CO_2 emissions from urea and limestone. This is explained by the double cropping system, which is more prevalent in central–western states, such as Mato Grosso and Goiás, and less in northern and southern ones, such as Bahia and Rio Grande do Sul, demanding varying quantities of synthetic fertilizer and limestone (see Tables 5, 6, S15 and S16 (Supporting Information)). The percentage difference between the highest and lowest emissions across states for first-crop corn, without accounting for dLUC, was 45% (Maranhão at 380.04 and Paraná at 287.37 kg CO_2e/t corn). Similarly to soybean, the results changed significantly with dLUC inclusion. Country-level emissions for first crop corn rose 125%, to 557.16 kg CO_2e/t corn, and the difference between extreme states increased to 320% (Maranhão and Paraná).

Comparing the graphs in Figure 2 of the life cycle GHG emissions and the crop yields across states indicated an inverse (negative) relationship between the two indicators (i.e., yields and emissions change in opposite directions: as yields increase, emissions decrease). This behavior can be observed for most states producing first crop corn, soybeans, and sugarcane. For second-crop corn, however, Paraná and Tocantins do not follow this tendency. However, in general, second crop corn presented significantly lower impacts than first crop corn, with −18% on average, considering the median values calculated for Brazil.

Emissions from dLUC are important contributors to the GHG emissions associated with the three agricultural production systems investigated. The dLUC values obtained for sugarcane are comparable to the other categories in most states while, for corn and soybean, dLUC is significantly greater than all other categories. These results are due to the patterns of cropland expansion over the 2000–2019 period, with 15% and 22% of the corn and soybean areas in 2019 originating from native vegetation in 2000, respectively [35]. dLUC is highly dependent on the 20-year inventory period, and as time passes, values can change substantially [51]. To reduce dLUC emissions, the most critical action is to change the expansion patterns of corn and soybean in the future, avoiding natural lands and prioritizing low-carbon agricultural areas, such as degraded pastures. Indeed, with decreasing deforestation rates in Brazil [70], increasing cultivation in the second crop [40], and growing commitments from the industry to cease sourcing from recently deforested areas [71], dLUC emissions are expected to decline in the future. In the more recent period, 2023–2023, the soybean area coming from natural vegetation has already been reduced by 18% compared with 2000–2019 [72]. Due to characteristics such as a non-recurrent nature, high variability, and high uncertainty [73,74], dLUC emissions are recommended to be reported separately from other categories [57].

Considering the uncertainties assigned to the emission factors of selected inputs and outputs (Table 2), the statistical analysis presented in Table S21 (Supporting Information) shows whether emissions between states are statistically significantly different. In the case of sugarcane, median and standard deviation values indicate that all states are statistically different from each other; however, the comparison between São Paulo and Brazil shows no significant difference. For soybean, the results for Paraná, Goiás, and Mato Grosso do Sul can be considered statistically similar, as can the results for Bahia, Brazil, and Mato Grosso. For corn, Brazil, Goiás, and Minas Gerais (first-crop) demonstrated similar results, as did São Paulo and Goiás (second-crop).

Our results—especially the information on the impacts of dLUC and the comparison between crop yields and emission impacts at the state level—can be particularly useful for national decarbonization programs, such as the ABC + Plan, which is the second phase of Brazil's Low-Carbon Crop and Livestock Production Plan [75]. The plan's main objective is to achieve emission reductions of 1.1 billion t CO_2e across 72 million ha, focusing on the integration of productive systems to improve soil quality, preserve forest areas, enhance agricultural practices, and increase carbon stocks, among numerous other actions. In this sense, the state-level information obtained in this study can help prioritize target areas with the potential to improve agricultural benefits and identify areas unsuitable for expansion, especially for crops directly linked to livestock systems, such as soybean. A report by de Lima et al. [76] explored the GHG mitigation potential of soybean cultivation, measuring the increase in carbon removal resulting from introducing forestry components in soybean crops through the implementation of a crop–forestry integration system in different scenarios for Brazil by 2030.

Furthermore, these findings could be impacted by policies focused on reducing the carbon footprint of agriculture in Brazil and globally. Once the data based on the deployment of these policies are available, they can be incorporated into crop inventories and/or dLUC estimates. Zero deforestation policies, such as the regulations within RenovaBio [32,33] and EU Deforestation-Free Products (EUDR) [77], if effective in reducing agriculture-associated deforestation in Brazil, could lead to significant reductions in dLUC emissions and, consequently, in total life cycle GHG emissions associated with crops.

The results from recent studies addressing decarbonization potential and opportunities for the country's agribusiness sector, combined with the findings of our study, have the potential to contribute to broader discussions. Brazil's National Bank of Development (BNDES) released a study presenting scenarios for the economy and highlighting the importance of policy instruments for progress in decarbonizing basic industries. That study listed numerous factors of advantage, such as the wide availability of land beyond its use for food production and biodiversity conservation, the high plant growth rate, and the proven capacity for large-scale production of certified biomass. A report by McKinsey & Company [78] explored Brazil's potential leadership role in decarbonization initiatives, developing scenarios to assess the mitigation potential of the different sectors, including agriculture, industry, and energy.

3.2.2. Comparison with Life Cycle GHG Emissions Calculated with Inventories from Other Sources

In this analysis, we excluded emissions from dLUC and infrastructure, in the case that any were included in the inventories (e.g., Agro-footprint v6.3 and Ecoinvent v3.9.1 databases). Figure 3 compares the life cycle GHG emissions of crop production from various studies.

In our study, the results for sugarcane are consistently higher than those reported in other sources. At the national and state levels, these differences can be attributed to the quantity of limestone used and the inclusion of various types of fertilizers in our analysis. For N, for example, we consider nine different fertilizer types, whereas Agri-footprint includes six. BioGrace, GHGenius, and Resolution 758 do not specify any type; therefore, we assumed urea as a proxy. As previously discussed in Section 3.2.1, each type of fertilizer presents distinct manufacturing emissions. For São Paulo, Ecoinvent clearly indicates in their documentation that all N fertilizer was assumed as urea (3.50 kg CO_2e/kg N). If we considered calcium nitrate (18.11 kg CO_2e/kg N) as the proxy for unspecified N fertilizers, instead of urea in BioGrace, GHGenius, and Resolution 758, the total impact of sugarcane would have increased from 28.74, 37.44, and 33.45 to 41.61, 57.24, and 49.15 kg CO_2e/t cane, respectively.

In contrast to sugarcane, our study yielded lower emissions for soybean than those from Agri-footprint, Ecoinvent, and Resolution 758. The significant difference in favor of Agri-footprint (+52%) at the national level can be largely attributed to the impact of soybean seed production in its database (i.e., soybean, start material, at seed production {BR}, with an impact of 7.72 kg CO_2e/kg) [53], which is significantly higher than the most likely value used in this study (i.e., soybean seed, for sowing {GLO}, with an impact of 0.43 kg CO_2e/kg) [38]. The production of soybean seeds accounts for 156.00 kg CO_2e/t soy, which is equivalent to 32% of the total soybean impact calculated using Agri-footprint, whereas, in our study, seed production accounts for 17.62 kg CO_2e/t soy, equivalent to 5% of the total impact. Similarly, the production of corn seed in Agri-footprint (i.e., maize, start material, at seed production {BR}, with 4.04 kg CO_2e/kg) [53] has a much higher impact (i.e., maize seed, at farm {GLO}, with 1.25 kg CO_2e/kg) than what we used as most likely, but lower than the considered maximum value (i.e., 2.81 kg CO_2e/kg) (Table 2).

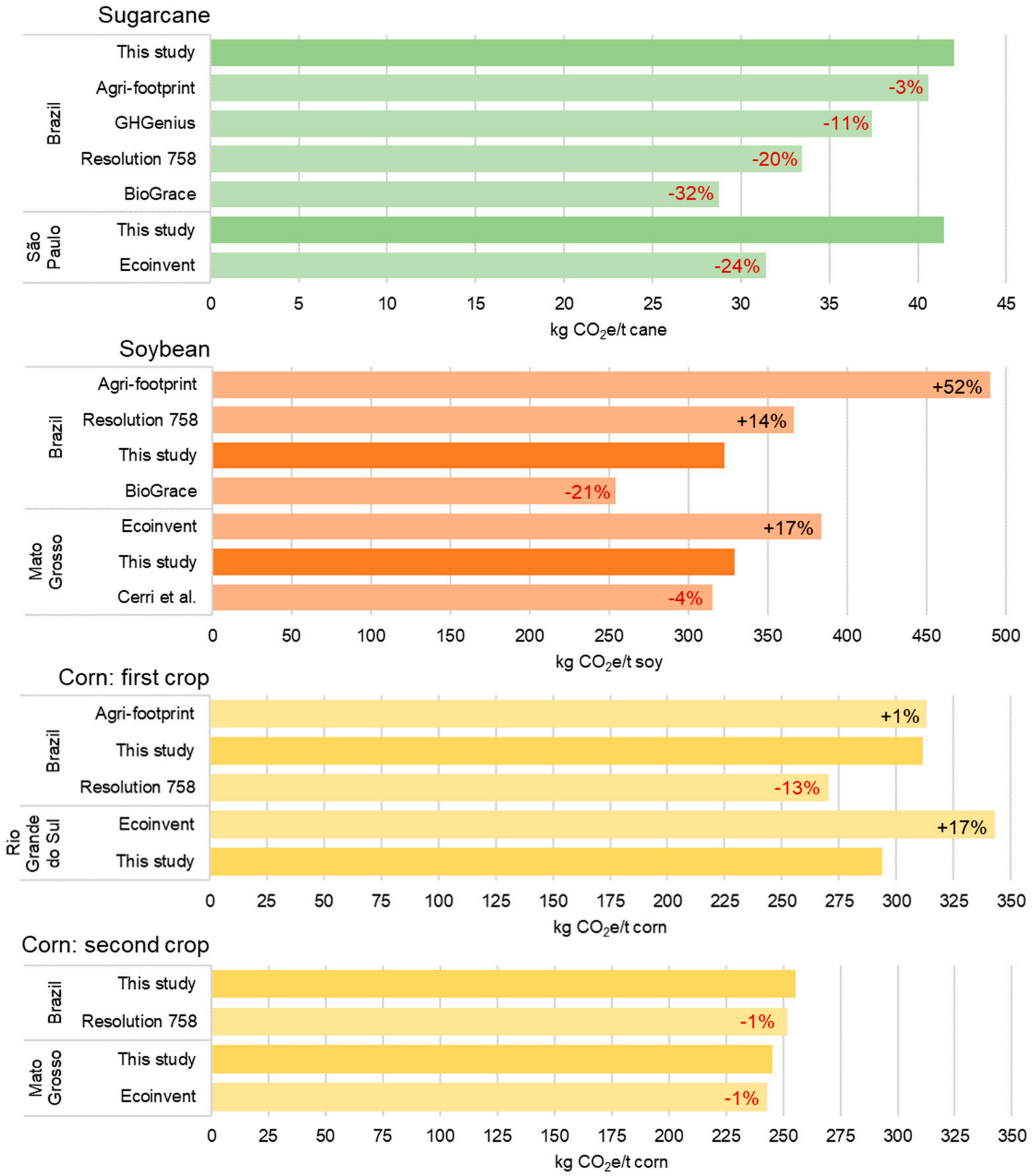

Figure 3. Comparison of life cycle GHG emissions of crop production from different sources (in kg CO_2e/t crop; median values for this study), excluding direct land use change (dLUC) emissions. Note the different values on the horizontal axes for each crop. Bars with darker colors refer to the results obtained in this study. The % values inside the bars indicate the difference between the emissions calculated in this study and those from the other sources. Sources: Agri-footprint v6.3 [53], BioGrace [52], Cerri et al. [54], GHGenius [22], and Ecoinvent v3.9.1 [38]. Emissions of Agri-footprint and Ecoinvent calculated using SimaPro v9.6.0.1 [55] and the IPCC 2021 GWP100 v1.02 method [42].

At the state level, for corn production (first crop) in Rio Grande do Sul, Ecoinvent includes processes of grain drying (i.e., drying of maize grain, with an impact of

36.70 kg CO_2e/m^3) and fertilizer and pesticide packaging (i.e., packaging, for fertilizers {GLO}, with an impact of 93.30 kg CO_2e/t, and packaging for pesticides {GLO}, with 332.00 kg CO_2e/t) [38], which are not included in our inventories. These processes combine to a total of 34.00 kg CO_2e/t corn (25.30 from drying and 8.60 from packaging), representing 10% of the corn production impact in the state. This would have leveled the results with our study if it had been excluded from the calculation. In the case of Mato Grosso, Ecoinvent does consider the impact of grain drying. For corn production in both states, we adjusted the amounts of limestone used to higher values than those presented in Ecoinvent (Table 7).

As discussed in Sections 3.1.2 and 3.2.2, the calculation of life cycle GHG emissions is highly sensitive to the inputs listed in the inventories and their corresponding emission factors. For this reason, in addition to adding a level of uncertainty to the emission factors of selected inputs and outputs (Table 2), we retrieved the most representative data available for the crops studied and made efforts to ensure that all information gathered and generated was presented as transparently as possible.

4. Conclusions

We successfully compiled state-level inventories for three key crops in Brazil that are used as feedstocks for various food products and biofuels, based on the most recent and representative data available. For sugarcane, we obtained information from the primary data submitted by biofuel producers to RenovaBio. For soybean and corn, we retrieved and updated data from a previous study, which gathered information through panel consultations with farmers and sector experts.

This study was limited by the reduced number of mills declaring primary data to RenovaBio, especially for corn and soybean production. However, as national policy and carbon footprint standards continue to develop, we expect more certified primary data for relevant crops to become available in the near future. Nevertheless, a comparison of the methodology and data sources of this study with commercial databases (e.g., Agrifootprint and Ecoinvent), which are typically used to assess the environmental impacts of food products and biofuels, shows that the inventories we generated rely on higher resolution and more detailed agricultural profiles, which probably led to their greater representativeness of the investigated crop production systems.

We observed variability in the life cycle GHG emissions of the crops across different states, more significantly for corn and sugarcane. Excluding emissions from dLUC, the percentage differences between the highest- and lowest-emitting states were 35% for sugarcane, 15% for soybean, and 45% for corn. When dLUC is included, particularly for soybean and corn, the variation increases greatly, and the ranking of states with the highest and lowest emission levels shifts.

The inventories generated in this study offer valuable support for a wide range of applications. The results can serve as key references in LCI databases, such as the inventories of agriculture, forestry, and animal husbandry in Brazil [20]; in the development of low-carbon policies, including the Low-Carbon Soybean program [79]; and in carbon footprint calculators, such as Footprint Pro Carbono [80]. For bioenergy policies such as RenovaBio, CORSIA, and IMO's GHG Strategy and Net Zero Framework, these inventories can help to establish default emission factors for the country and its states, improving the accuracy and granularity of GHG emission data profiles. This enhanced precision could significantly support the management of supply chains aimed at decarbonization and identify regions, farmers, and biofuel producers excelling in sustainable best practices. Therefore, we strongly encourage the use of these inventories at both state and national levels to inform decision-making within international biofuel regulatory frameworks and to assess the sustainability and environmental impacts of food production across emerging platforms.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17188482/s1, Figure S1: Average state participation and yield of the harvested area of the three crops investigated (i.e., corn and soybean (2017–2019), and sugarcane (2019–2021)); Table S1: Sugarcane data for all states from IBGE (2024) [2] (annual average for 2019–2021); Table S2: Sugarcane data for all states from Conab (2024) [3] (annual average for 2019–2021); Table S3: Data on sugarcane production in Brazil for different states (average values for the period of 2019–2021); Table S4: Data of soybean production in Brazil for different states (2017–2019 average); Table S5: Soybean data for all states from IBGE (2024) [2] (annual average for 2017–2019); Table S6: Soybean data for all states (annual average for 2017–2019) (Conab, 2024 [3]); Table S7: Microregions of soybean (annual average for 2017–2019) (Hirakuri et al., 2019 [31]); Table S8: Data on corn production in Brazil for different states (2017–2019 average); Table S9: Corn data for all states from IBGE (2024) [2] (annual average for 2017–2019); Table S10: Corn data for all states from Conab (2024) [3] (annual average for 2017–2019); Table S11: Microregions of corn (annual average for 2017–2019) (Hirakuri et al., 2019 [31]); Table S12: Life cycle GHG emissions of selected inputs considered in the agricultural stage of sugarcane, soybean, and corn production; Section: Calculation of direct and indirect N_2O emissions; Table S13: State-level inventory of sugarcane production in Brazil (2019–2021); Table S14: Inventory of soybean production in Brazil for different states (2017–2019); Table S15: Inventory of first crop corn production in Brazil for different states (2017–2019); Table S16: Inventory of second crop corn production in Brazil for different states (2017–2019); Table S17: Life cycle GHG emissions of sugarcane production by state and category (median values in kg CO_2e/t cane); Table S18: Life cycle GHG emissions of soybean production by state and category (median values kg CO_2e/t soy); Table S19: Life cycle GHG emissions of first crop corn production by state and category (median values in kg CO_2e/t corn); Table S20: Life cycle GHG emissions of second crop corn production by state and category (median values in kg CO_2e/t corn); Table S21: Life cycle GHG emissions of the crops studied by state (in kg CO_2e/t crop), considering a 90% confidence interval (5th percentile, 25th percentile, median, 75th percentile, and 95th percentile).

Author Contributions: Conceptualization, L.G.P. and N.P.R.; Methodology, L.G.P., N.P.R., A.L.M.T.P., R.M.L.N. and M.I.S.F.; Formal analysis, L.G.P., N.P.R., A.L.M.T.P., R.M.L.N., J.E.A.S., H.D., M.H.H. and M.I.S.F.; Writing—original draft, L.G.P. and N.P.R.; Writing—review & editing, A.L.M.T.P., R.M.L.N., J.E.A.S., H.D., M.H.H. and M.I.S.F.; Visualization, L.G.P.; Supervision, M.I.S.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [Financiadora de Estudos e Projetos] grant number [1028—FAPED/CNPMA/FINEP—Renovacalc 01.22.0591.00 (1514/22)].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author(s).

Acknowledgments: The authors thank Mateus Ferreira Chagas (Brazilian Biorenewables National Laboratory), Natalia Crespo Mendes and João Paulo Savioli (Embrapa Environment), Rubens Augusto de Miranda and Alexandre Ferreira da Silva (Embrapa Maize and Sorghum), Marcelo Morandi (Embrapa International Relations), Maria Auxiliadora Nobre and Joana Borges da Rosa (Brazilian National Agency for Petroleum, Natural Gas, and Biofuels), and all stakeholders consulted for their valuable contributions to this study.

Conflicts of Interest: Lucas G. Pereira, Nilza Patrícia Ramos, Anna Leticia M.T. Pighinelli, Renan M.L. Novaes and Marília I.S. Folegatti were employed by Embrapa Environment, and Henrique Debiasi and Marcelo H. Hirakuri were employed by Embrapa Soybean. Embrapa is the Brazilian Agricultural Research Corporation, a federal research institute affiliated with the Ministry of Agriculture, Livestock and Supply. The remaining author, Joaquim E.A. Seabra, declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

%	percentage
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
dLUC	direct land use change
GHG	greenhouse gas
ha	hectare
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
kg	kilogram
kha	kilohectare
LCA	life cycle assessment
Mt	million metric tons
N	nitrogen
N_2O	nitrous oxide
SAFs	sustainable aviation fuels
t	metric ton
t cane	metric ton of sugarcane
t soy	metric ton of soybean
t corn	metric ton of corn

References

1. FAO FAOSTAT Database. Crop and Livestock Products—2023. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 28 April 2025).
2. IBGE. Municipal Agricultural Production. Available online: https://sidra.ibge.gov.br/pesquisa/pam/tabelas (accessed on 7 March 2024).
3. Conab Crop Harvests in Brazil. Available online: https://www.conab.gov.br/info-agro/safras (accessed on 25 September 2024).
4. Brazilian National Agency for Petroleum, Natural Gas, and Biofuels. Dynamic Panel—Biodiesel Production. Available online: https://app.powerbi.com/view?r=eyJrIjoiOTlkODYyODctMGJjNS00MGIyLWJmMWItNGJlNDg0ZTg5NjBlIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9&pageName=ReportSection8aa0cee5b2b8a941e5e0%22 (accessed on 19 February 2025).
5. Brazilian National Agency for Petroleum, Natural Gas, and Biofuels. Dynamic Panel—Ethanol Production. Available online: https://app.powerbi.com/view?r=eyJrIjoiMmRhZWU2NDUtZWE2Yi00NzI5LWJjMGQtNjIwNjE0MjM0MjEzIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9 (accessed on 19 February 2025).
6. International Energy Agency. Transport Biofuels. Available online: https://www.iea.org/reports/renewables-2023/transport-biofuels (accessed on 25 September 2024).
7. Unica UnicaData. Ethanol Production. Available online: https://unicadata.com.br/ (accessed on 25 September 2024).
8. Conab Produção de Cana-de-Açúcar Na Safra 2023/24 Chega a 713,2 Milhões de Toneladas, a Maior Da Série Histórica. Available online: https://www.conab.gov.br/ultimas-noticias/5489-producao-de-cana-de-acucar-na-safra-2023-24-chega-a-713-2-milhoes-de-toneladas-a-maior-da-serie-historica#:~:text=J%C3%A1%20o%20etanol%20de%20milho,em%20rela%C3%A7%C3%A3o%20%C3%A0%20safra%20anterior (accessed on 3 December 2024).
9. *ISO 14040*; Environmental Management—Life-Cycle Assessment—Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 25 September 2024).
10. *ISO 14044*; Environmental Management—Life-Cycle Assessment—Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/38498.html (accessed on 25 September 2024).
11. Yang, Y. Toward a More Accurate Regionalized Life Cycle Inventory. *J. Clean. Prod.* **2016**, *112*, 308–315. [CrossRef]
12. Islam, S.; Ponnambalam, S.G.; Lam, H.L. Review on Life Cycle Inventory: Methods, Examples and Applications. *J. Clean. Prod.* **2016**, *136*, 266–278. [CrossRef]
13. Shi, S.; Yan, X. A Critical Review on Spatially Explicit Life Cycle Assessment Methodologies and Applications. *Sustain. Prod. Consum.* **2024**, *52*, 566–579. [CrossRef]

14. Beloin-Saint-Pierre, D.; Albers, A.; Hélias, A.; Tiruta-Barna, L.; Fantke, P.; Levasseur, A.; Benetto, E.; Benoist, A.; Collet, P. Addressing Temporal Considerations in Life Cycle Assessment. *Sci. Total Environ.* **2020**, *743*, 140700. [CrossRef] [PubMed]
15. Liu, M.; Zhu, G.; Tian, Y. The Historical Evolution and Research Trends of Life Cycle Assessment. *Green Carbon* **2024**, *2*, 425–437. [CrossRef]
16. Dai, T.; Fleischer, A.S.; Lee, R.; Wemhoff, A.P. Life Cycle Inventory Regionalization and Uncertainty Characterization: A Multilevel Modeling Approach. *J. Clean. Prod.* **2020**, *242*, 118459. [CrossRef]
17. Heijungs, R. Spatial differentiation, GIS-based regionalization, hyperregionalization, and the boundaries of LCA. In *Environment and Energy*; Ioppolo, G., Ed.; FrancoAngeli: Milano, Italy, 2012; pp. 165–176.
18. Matsuura, M.I.S.F.; May, A.; de Castro, C.; Bungenstab, D.J.; Sugawara, E.T.; Dias, F.R.T.; Lansche, J.; Hirakuri, M.; de Figueirêdo, M.C.B.; Chagas, M.F.; et al. Life Cycle Inventories of Brazilian Agricultural Products: A Contribution to the Ecoinvent Database—ICVAgroBR. Available online: https://www.embrapa.br/en/busca-de-noticias/-/noticia/18262026/partners-formalize-technical-cooperation-for-life-cycle-assessment-studies (accessed on 25 November 2024).
19. Ecoinvent. Ecoinvent Database v3.6. Available online: https://support.ecoinvent.org/ecoinvent-version-3.6 (accessed on 26 November 2024).
20. Matsuura, M.I.S.F.; Picoli, J.F. Life Cycle Inventories of Agriculture, Forestry and Animal Husbandry—Brazil: For the SRI Project. Available online: https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1113475/1/LCI-Agriculture-2018.pdf (accessed on 25 September 2024).
21. Ramos, N.P.; Mendes, N.C.; Folegatti, M.I.S.; Bayma, G.; Novaes, R.M.L.; Morandi, M.A.B.; Pighinelli, A.L.M.T.; Savioli, J.P.P.D.; Buffon, V.B. Regionalization of Typical Profiles of Corn, Soybean, and Sugarcane. Available online: https://www.gov.br/anp/pt-br/assuntos/renovabio/arq/arquivos-estudos-relatorio-e-seminarios/ (accessed on 3 December 2024).
22. S&T Squared. GHGenius, 5.02b. Available online: https://www.ghgenius.ca/ (accessed on 9 February 2024).
23. Pelton, R. Spatial Greenhouse Gas Emissions from US County Corn Production. *Int. J. Life Cycle Assess.* **2019**, *24*, 12–25. [CrossRef]
24. Yang, Y.; Tao, M.; Suh, S. Geographic Variability of Agriculture Requires Sector-Specific Uncertainty Characterization. *Int. J. Life Cycle Assess.* **2018**, *23*, 1581–1589. [CrossRef]
25. International Energy Agency. Carbon Accounting for Sustainable Biofuels. Available online: https://www.iea.org/reports/carbon-accounting-for-sustainable-biofuels (accessed on 9 February 2024).
26. ICAO. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Available online: https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx (accessed on 9 February 2024).
27. IMO. Study on the Readiness and Availability of Low- and Zero-Carbon Ship Technology and Marine Fuels. Available online: https://wwwcdn.imo.org/localresources/en/MediaCentre/WhatsNew/Documents/MEPC80.INF10.pdf (accessed on 9 February 2024).
28. Hestia. Data and Models for More Sustainable Agriculture. Available online: https://www.hestia.earth/ (accessed on 16 October 2024).
29. Trase. Intelligence for Sustainable Trade. Available online: https://trase.earth/ (accessed on 16 October 2024).
30. IPCC Intergovernmental Panel on Climate Change. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019.
31. Hirakuri, M.H.; Conte, O.; Prando, A.M.; Castro, C.; Balbinot, A.A., Jr. Diagnosis of Soybean Production in Soybean Macroregions 1, 2, 3, 4, and 5. Available online: https://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1118962 (accessed on 19 August 2025). (In Portuguese).
32. Brazil Bill 15,082. Available online: https://legislacao.presidencia.gov.br/atos/?tipo=LEI&numero=15082&ano=2024&ato=457QzaE1UNZpWT7e9 (accessed on 15 February 2025).
33. Brazil Bill 13,576. Available online: https://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm (accessed on 25 September 2024).
34. Brazilian National Agency for Petroleum, Natural Gas, and Biofuels. Resolution 758. Available online: https://atosoficiais.com.br/anp/resolucao-n-758-2018-regulamenta-a-certificacao-da-producao-ou-importacao-eficiente-de-biocombustiveis-de-que-trata-o-art-18-da-lei-no-13-576-de-26-de-dezembro-de-2017-e-o-credenciamento-de-firmas-inspetoras?origin=institui (accessed on 5 February 2025).
35. Garofalo, D.F.T.; Novaes, R.M.L.; Pazianotto, R.A.A.; Maciel, V.G.; Brandão, M.; Shimbo, J.Z.; Folegatti-Matsuura, M.I.S. Land-Use Change CO_2 Emissions Associated with Agricultural Products at Municipal Level in Brazil. *J. Clean. Prod.* **2022**, *364*. [CrossRef]
36. Embrapa. Brazilian Land Use Change Method. Available online: https://brluc.cnpma.embrapa.br/ (accessed on 2 May 2024).
37. Brazilian National Agency for Petroleum, Natural Gas, and Biofuels. Certification of Efficient Production or Import of Biofuels. Available online: https://www.gov.br/anp/pt-br/assuntos/renovabio/certificados-producao-importacao-eficiente-biocombustiveis (accessed on 19 February 2025).
38. Ecoinvent Ecoinvent Database v3.9.1. Available online: https://ecoinvent.org/the-ecoinvent-database/ (accessed on 2 May 2024).

39. GFLI Global Feed LCA Institute (GFLI) Database. Available online: https://globalfeedlca.org/gfli-database/ (accessed on 25 September 2024).
40. Novaes, R.M.L.; Tubiello, F.N.; Garofalo, D.F.T.; de Santis, G.; Pazianotto, R.A.A.; Matsuura, M.I.S.F. *Brazil's Agricultural Land, Cropping Frequency and Second Crop Area: FAOSTAT Statistics and New Estimates*; Embrapa Environment: Jaguariuna, Brazil, 2022.
41. Embrapa. Systems of Corn Production. Available online: https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/milho/producao/sistemas-diferenciais-de-cultivo (accessed on 8 August 2024).
42. IPCC. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Shukla, P.R., Skea, J., Slade, R., Khourdajie, A., Al Diemen, R., van McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2022, ISBN 9781009157926.
43. IPCC. *N_2O Emissions from Managed Soils, and CO_2 Emissions from Lime and Urea Application*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2006.
44. Matsuura, M.I.S.F.; Scachetti, M.T.; Chagas, M.F.; Seabra, J.E.A.; Bonomi, A.M.; Bayma, G.; Picoli, J.F.; Morandi, M.A.B.; Ramos, N.P.; Cavalett, O.; et al. RenovaCalc: Method and Tool to Account for the Carbon Intensity of Biofuels under the RenovaBio Program. Technical Report. Available online: 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 on 25 September 2024). (In Portuguese)
45. ANL Argonne National Laboratory. GREET Model. Available online: https://greet.anl.gov/ (accessed on 25 September 2024).
46. Lumivero. Software @Risk v7.5. Available online: https://lumivero.com/products/at-risk/ (accessed on 2 February 2025).
47. ANL Argonne National Laboratory. R&D GREET 2024. Available online: https://greet.anl.gov/index.php?content=greetdotnet (accessed on 9 February 2025).
48. ISCC International Sustainability & Carbon Certification. ISCC EU 205. Greenhouse Gas Emissions. Available online: https://www.iscc-system.org/wp-content/uploads/2022/05/ISCC_EU_205_Greenhouse-Gas-Emissions-v4.0.pdf (accessed on 25 August 2025).
49. Ecoinvent. Ecoinvent Database v3.7. Available online: https://support.ecoinvent.org/ecoinvent-version-3.7 (accessed on 25 August 2025).
50. EU. JEC (JRC-Eucar-Concawe) E3-Database. Available online: https://biograce.net/content/ghgcalculationtools/methodology (accessed on 9 February 2025).
51. Maciel, V.G.; Novaes, R.M.L.; Brandão, M.; Cavalett, O.; Pazianotto, R.A.A.; Garofalo, D.T.; Folegatti-Matsuura, M.I.S. Towards a Non-Ambiguous View of the Amortization Period for Quantifying Direct Land-Use Change in LCA. *Int. J. Life Cycle Assess.* **2022**, *27*, 1299–1315. [CrossRef]
52. EU. BioGrace. Available online: http://www.biograce.net/content/ghgcalculationtools/recognisedtool/ (accessed on 20 April 2017).
53. Blonk. Consultants Agri-Footprint v6.3. Available online: https://blonksustainability.nl/tools-and-databases/agri-footprint (accessed on 17 October 2024).
54. Cerri, C.E.P.; You, X.; Cherubin, M.R.; Moreira, C.S.; Raucci, G.S.; Castigioni, B.d.A.; Alves, P.A.; Cerri, D.G.P.; Mello, F.F.d.C.; Cerri, C.C. Assessing the Greenhouse Gas Emissions of Brazilian Soybean Biodiesel Production. *PLoS ONE* **2017**, *12*, e0176948. [CrossRef]
55. Pré Sustainability SimaPro v9.6.0.1. Available online: https://simapro.com/ (accessed on 17 October 2024).
56. Liu, X.; Kwon, H.; Wang, M.; O'Connor, D. Life Cycle Greenhouse Gas Emissions of Brazilian Sugar Cane Ethanol Evaluated with the GREET Model Using Data Submitted to RenovaBio. *Environ. Sci. Technol.* **2023**, *57*, 11814–11822. [CrossRef]
57. *ISO 14067:2018*; Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification. ISO: Geneva, Switzerland, 2018. Available online: https://www.iso.org/standard/71206.html (accessed on 15 May 2025).
58. Daioglou, V.; Woltjer, G.; Strengers, B.; Elbersen, B.; Barberena Ibañez, G.; Sánchez, G.D.; Gil, B.J.; van Vuuren, D.P. Progress and Barriers in Understanding and Preventing Indirect Land-use Change. *Biofuels Bioprod. Biorefin.* **2020**, *14*, 924–934. [CrossRef]
59. Pendrill, F.; Gardner, T.A.; Meyfroidt, P.; Persson, U.M.; Adams, J.; Azevedo, T.; Bastos Lima, M.G.; Baumann, M.; Curtis, P.G.; De Sy, V.; et al. Disentangling the Numbers behind Agriculture-Driven Tropical Deforestation. *Science* **2022**, *377*, eabm9267. [CrossRef]
60. Seixas, C.D.S.; Neumaier, N.; Balbinot, J.A.A.; Krzyzanowski, F.C.; Leite, R.M.V.B.d.C. *Tecnologias de Produção de Soja*; Embrapa Soybean: Londrina, Brazil, 2020.
61. International Fertilizer Association. IFASTAT: Consumption of Fertilizers. Available online: https://www.ifastat.org/databases/plant-nutrition (accessed on 22 October 2024).
62. Macedo, I.C.; Seabra, J.E.A.; Silva, J.E.A.R. Green House Gases Emissions in the Production and Use of Ethanol from Sugarcane in Brazil: The 2005/2006 Averages and a Prediction for 2020. *Biomass Bioenergy* **2008**, *32*, 582–595. [CrossRef]

63. Macedo, I.C.; Leal, M.R.L.V.; da Silva, J. Greenhouse Gases Emissions in the Production and Use of Ethanol from Sugarcane in Brazil. Available online: https://repositorio.cetesb.sp.gov.br/handle/123456789/3852 (accessed on 25 September 2024).
64. Seabra, J.E.A.; Macedo, I.C.; Chum, H.L.; Faroni, C.E.; Sarto, C.A. Life Cycle Assessment of Brazilian Sugarcane Products: GHG Emissions and Energy Use. *Biofuels Bioprod. Biorefin.* **2011**, *5*, 519–532. [CrossRef]
65. IDEA. *Sugarcane Agroindustry Performance Indicators: Crops 2012/2013 and 2013/2014*; IDEA: Ribeirão Preto, Brazil, 2014.
66. Cavalett, O.; Chagas, M.F.; Magalhães, P.S.G.; Carvalho, J.L.N.; Cardoso, T.F.; Franco, H.C.J.; Braunbeck, O.A.; Bonomi, A. The Agricultural Production Model. In *Green Energy and Technology: Virtual Biorefinery. An Optimization Strategy for Renewable Carbon Valorization*; Bonomi, A.M., Cavalett, O., da Cunha, M.P., Lima, M.A.P., Eds.; Springer International Publishing: Cham, Switzerland, 2016; pp. 13–51.
67. Pereira, L.G.; Cavalett, O.; Bonomi, A.; Zhang, Y.; Warner, E.; Chum, H.L. Comparison of Biofuel Life-Cycle GHG Emissions Assessment Tools: The Case Studies of Ethanol Produced from Sugarcane, Corn, and Wheat. *Renew. Sustain. Energy Rev.* **2019**, *110*, 1–12. [CrossRef]
68. Guarenghi, M.M.; Garofalo, D.F.T.; Seabra, J.E.A.; Moreira, M.M.R.; Novaes, R.M.L.; Ramos, N.P.; Nogueira, S.F.; de Andrade, C.A. Land Use Change Net Removals Associated with Sugarcane in Brazil. *Land* **2023**, *12*, 584. [CrossRef]
69. Escobar, N.; Tizado, E.J.; zu Ermgassen, E.K.H.J.; Löfgren, P.; Börner, J.; Godar, J. Spatially-Explicit Footprints of Agricultural Commodities: Mapping Carbon Emissions Embodied in Brazil's Soy Exports. *Glob. Environ. Change* **2020**, *62*, 102067. [CrossRef]
70. Mongabay. Amazon Deforestation in Brazil Plunges 31% to Lowest Level in 9 Years. Available online: https://news.mongabay.com/2024/11/amazon-deforestation-in-brazil-plunges-31-to-lowest-level-in-9-years/ (accessed on 15 May 2025).
71. Gonçalves, C.K.; Monteiro, L.; Bovee, V.; Arceo, N.M.P. Companies Collaborating for Sustainable Soy Landscapes: Progress and Transition Pathways. Available online: https://weforum.ent.box.com/s/hheie7132493v78f0logfufx8i213t7z (accessed on 15 May 2025).
72. MapBiomas Land Cover and Use. Coverage and Transitions Statistics by Biomes—MapBiomas Brasil Collection 9. Available online: https://data.mapbiomas.org/dataset.xhtml?persistentId=doi:10.58053/MapBiomas/7VJZWK (accessed on 15 May 2025).
73. Donke, A.C.G.; Novaes, R.M.L.; Pazianotto, R.A.A.; Moreno-Ruiz, E.; Reinhard, J.; Picoli, J.F.; da Folegatti-Matsuura, M.I.S. Integrating Regionalized Brazilian Land Use Change Datasets into the Ecoinvent Database: New Data, Premises and Uncertainties Have Large Effects in the Results. *Int. J. Life Cycle Assess.* **2020**, *25*, 1027–1042. [CrossRef]
74. van Middelaar, C.E.; Cederberg, C.; Vellinga, T.V.; van der Werf, H.M.G.; de Boer, I.J.M. Exploring Variability in Methods and Data Sensitivity in Carbon Footprints of Feed Ingredients. *Int. J. Life Cycle Assess.* **2013**, *18*, 768–782. [CrossRef]
75. Brazil Targets of ABC+. Available online: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/planoabc-abcmais/abc/metas-do-abc (accessed on 1 September 2025).
76. de Lima, C.Z.; Estevam, C.G.; Pavão, E.M.; Pinto, T.P.; Assad, E.D. *Greenhouse Gases Mitigation Potential of Soy Farming: Decarbonization Actions to Be Taken by 2030*; FGV-EESP: São Paulo, Brazil, 2022.
77. EU. Deforestation-Free Products. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52025XC04524 (accessed on 25 September 2024).
78. McKinsey & Company. Beyond Net Zero: Brazil's Massive Opportunity to Decarbonize the World. Available online: https://www.mckinsey.com.br/our-insights/all-insights/beyond-net-zero-brazils-massive-opportunity-to-decarbonize-the-world (accessed on 3 September 2025).
79. Nepomuceno, A.L.; Balbinot, A.A., Jr.; Rufino, C.F.G.; Debiasi, H.; Nogueira, M.A.; Franchini, J.C.; Alves, F.V.; Carnevalli, R.A.; de Almeida, R.G.; Bungenstab, D.J.; et al. *LCS Program-Low Carbon Soybean: A New Concept of Sustainable Soybean*; Embrapa Soja: Londrina, Brazil, 2023.
80. Matsuura, M.I.S.F.; Savioli, J.P.D.; Pighinelli, A.L.M.T.; Ramos, N.P.; Novaes, R.M.; Hiramoto, T.E.; Ferreira, R.P.; Anselmi, A. Footprint Pro Carbono. Available online: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/1162996/footprint-pro-carbono-a-calculadora-para-a-pegada-de-carbono-de-commodities-agricolas (accessed on 16 October 2024).