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Final Work Report

RenovaBio

REGIONALIZATION OF "TYPICAL" SUGARCANE PRODUCTION PROFILES FOR USE IN RENOVABIO

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Jaguariúna, SP
June 2024

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Summary

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Summary

RenovaBio is a policy designed to promote the decarbonization of Brazil's transport sector by encouraging the use of biofuels with superior energy-environmental efficiency compared to fossil fuels. Its structure covers filling fields for the various production stages of ethanol, biodiesel, biomethane and aviation biokerosene, following the product Life Cycle Assessment methodology. For ethanol production, producers using sugarcane or corn as raw materials can input either "primary data" (specific to their current production system) or default data (typical system data with added penalties for unverifiable information). The current profile of the typical sugarcane system represents national-scale production, which may not accurately reflect the diversity of production practices across Brazil's different regions. This study aimed to characterize "typical" sugarcane production systems, considering the reality of the different Brazilian producing regions. The goal was to create "regionalized default" data profiles for use in RenovaCalc, incorporating penalties where necessary. This approach aligns with policy objectives: (i) encouraging the use of "primary data" in RenovaCalc and (ii) maintaining transparency in the methodology and parameters used. The methodology involved identifying Brazilian states with sugarcane stalk production ≥ 1% of the national total, utilizing certified primary agricultural databases from RenovaCalc to characterize state-level production practices. Carbon intensity (CI) simulations were then conducted using both the current version of RenovaCalc (7.0) and an upcoming improved version (9.0).

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Eight states were initially identified as significant sugarcane producers. However, sufficient data in RenovaCalc allowed for the characterization of “typical” profiles for ten states (SP, GO, MG, MS, PR, MT, AL, PE, PB and BA). The CI of these state profiles ranged from 34.5 to 46.7 kgCO_2eq/t sugarcane stalks, while the national profile currently adopted is 33.5 kgCO_2eq/t sugarcane stalks, using RenovaCalc 7.0. In the simulation using RenovaCalc 9.0, the CI ranged from 36.9 to 53.5 kgCO_2eq/t of sugarcane stalks, which is also higher than the current national profile. It is concluded that updating the “typical” profile to consider state-level data better represents the production conditions of Brazilian sugarcane and is recommended for use in RenovaCalc, following the application of penalties as outlined in the policy regulations. Using sugarcane production efficiency indices, obtained from certifications for first-generation ethanol from sugarcane (1GS) and first-generation ethanol from a flex plant (1GFlex) within RenovaCalc, ensures accuracy and credibility in representing production profiles. This takes into account the technologies and innovations adopted by the sugarcane sector under RenovaBio. It is recommended to maintain this procedure in future updates, aligning with the time intervals of other policy initiatives, while adhering to RenovaBio's core principles.

Index terms: *Sacchrarum spp;* production system; greenhouse gas emissions; carbon intensity.

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1. Introduction

1.1. RenovaBio

The effects of climate change are increasingly evident as society experiences more frequent extreme events around the globe. The rise in global average temperature is now a reality, and mitigating and adapting to its effects require heightened efforts from both governments and society to prevent the temperature increase from exceeding 1.5 degrees Celsius. Globally, the energy sector is the largest contributor to greenhouse gas (GHG) emissions due to the reliance on fossil fuels. In Brazil, the energy sector ranks third in GHG emissions, contributing 424 GgCO_2eq in 2016, with 95.3% of this attributed to the fuel sector (Brazil, 2021). Despite having a relatively clean energy matrix compared to other nations, the Brazilian government has committed to including the energy sector in its international GHG mitigation commitments (Nationally Determined Contribution, NDC), in line with the Paris Agreement.

Brazil has committed to reducing emissions by 37% by 2025 and 50% by 2050, relative to its 2005 levels (Brazil, 2022). Achieving these targets requires a multifaceted strategy, including expanding the share of renewable energy to 45% of the national energy matrix and increasing the use of biofuels. To support these efforts, the National Biofuels Policy, RenovaBio (Brasil, 2017 - Law 13,576, December 26, 2017), was enacted to promote the integration of sustainably produced biofuels into Brazil's energy matrix.

Biofuels with demonstrated energy-environmental efficiency—meaning lower GHG emissions per MJ over their life cycle compared to fossil fuel alternatives—are eligible for decarbonization credits (CBIOs) under the policy. These credits, equivalent to 1 (one) ton of CO_2eq avoided, can be traded in the financial market, providing additional income for producers (MME, 2017).

The biofuels covered under RenovaBio include first and second-generation ethanol, biodiesel, biomethane, and aviation biokerosene (ANP, 2023). To access CBIOs, these biofuels must demonstrate the eligibility of their biomass

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and energy-environmental efficiency in production, which is calculated using RenovaCalc, the policy's official tool (Matsuura et al., 2018).

Certification under RenovaBio also requires proving compliance with eligibility criteria for energy raw materials, aligned with existing environmental laws such as the Forest Code and the Agroecological Zoning of Oil Palm. A crucial requirement is that energy biomass must be produced on farms with an active (or pending) Rural Environmental Registration (CAR) and in areas where native vegetation has not been cleared since November 2018. This date marks the publication of RESOLUTION No. 758/2018 by the National Agency for Petroleum, Natural Gas and Biofuels (ANP), which is one of the instruments regulating RenovaBio (ANP, 2023).

This risk management mechanism is designed to prevent the expansion of energy biomass production into areas with native vegetation, thereby avoiding GHG emissions associated with land-use change.

Carbon accounting in RenovaCalc adheres to the principles of Life Cycle Assessment (LCA) as standardized by ISO 14040:2006, ISO 14044:2006 (ISO, 2006a, b), and ISO 14067:2018 (ISO, 2018). This comprehensive approach considers emissions from all stages of the biofuel life cycle, providing a detailed database that includes the carbon intensity of agricultural inputs, fuels and electricity. It covers emissions through the agricultural, industrial, and distribution stages, each with specific data entry structures (Figure 1), and incorporates values from scientific literature for the fuel consumption stage in vehicle engines.

Data entry for calculating the carbon intensity (CI) at the agricultural stage in RenovaCalc offers the option of using either "primary" data or "default" data for sugarcane, corn, and soybeans (Matsuura et al., 2018), with plans to incorporate oil palm, cotton, and other feedstocks. For the “primary data” option, fields include information on area, production, impurities, and agricultural inputs (such as soil correctives, chemical and organic fertilizers, fuels, and other energy sources) used in biomass production.

Utilizing “primary data” requires a comprehensive verification process during certification, encompassing a detailed set of data that describes the agricultural production profile. The default data option, on the other hand, involves a more limited set of verifiable data, where the agricultural production profile is based on a predefined value that represents a typical biomass production profile. This default data includes an added "penalty" to prevent underestimation of emissions. Verification for default data only requires confirming the area and production. It is important to note that the default data option should be used only when verifiable information for all parameters requested by the calculation tool is not available.

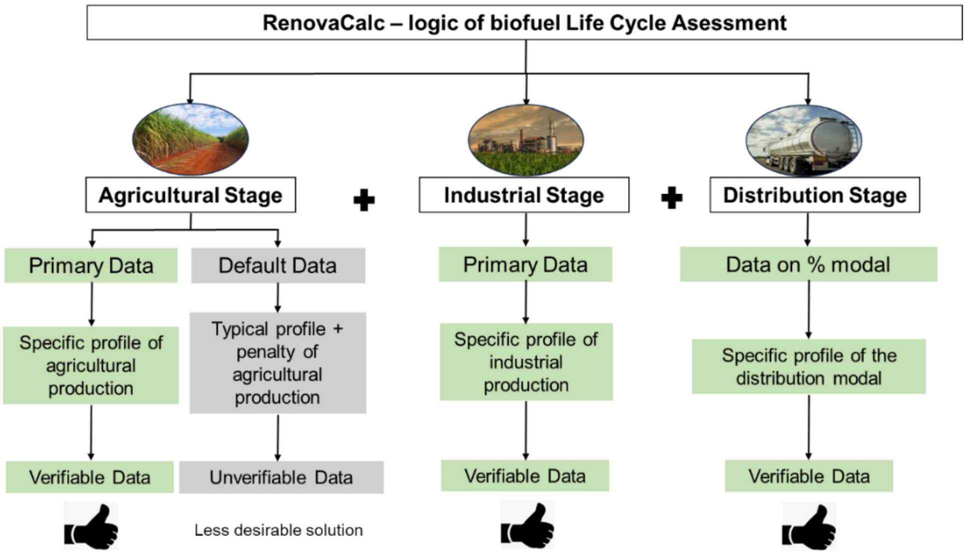

Figure 1. Simplified diagram of the sugarcane ethanol production stages considered in RenovaCalc, indicating the type of data required and the need for verification.

At the industrial stage, only "primary" data can be used, with fields for inputting yields from products and co-products, as well as the consumption of industrial inputs, electricity, and other energy sources. In the distribution stage, emission calculations are based on declared transport modes, following predefined profiles (Matsuura et al., 2018).

The data penalization approach for the agricultural stage ensures that, in the absence of primary, verifiable, and auditable information, there is no overestimation of GHG emissions. This approach helps ensure that each CBIO genuinely represents the avoidance of 1 ton of CO_2eq, thus preventing "greenwashing."

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1.2. Sugarcane as raw material at RenovaCalc

Brazil has long held the title of the world's largest producer of sugarcane, generating 724 million tons of stalks in 2022 (FAO, 2024), which accounted for approximately 38% of the global total. Within Brazil, sugarcane ranks fourth in the gross value of agricultural production, trailing only soybeans, cattle, chicken, and corn. In 2023, the sugarcane industry contributed R$ 111.2 billion from a cultivated area of 9.6 million hectares. The state of São Paulo leads in production with 4.7 million hectares dedicated to sugarcane, followed by Goiás and Minas Gerais, which vie for second place. Together, these states produced 76% of Brazil's sugarcane in the 2023 harvest, according to CONAB (2023).

The diversity of products derived from sugarcane (Figure 2) significantly enhances the profitability and sustainability of the sugar-energy chain. While sugar and ethanol are the primary outputs, bioelectricity, organic fertilizers (such as vinasse and filter cake), and yeast also make substantial contributions (Rossetto et al., 2022). Additionally, sugarcane is integral to green chemistry, yielding various other products that contribute to this sector (Cherubini, 2010).

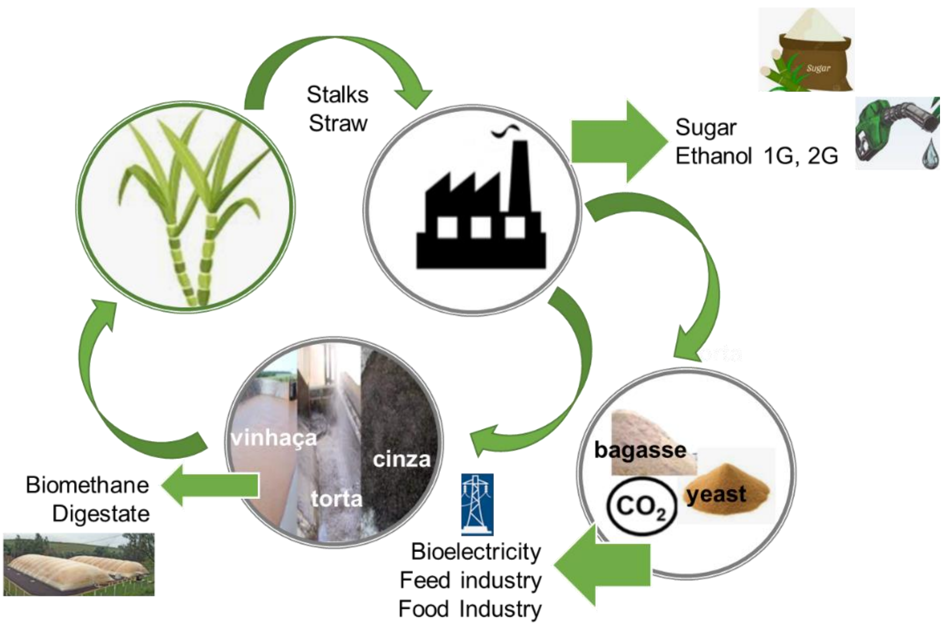

Figure 2. Representation of products generated from the industrial processing of sugarcane, contributing to the circular economy.

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Brazilian ethanol holds a prominent position in the global biofuels market, ranking second only to American ethanol (USDA, 2024). This underscores its vital contribution to sustainability in the energy sector. The advent of second-generation technology, which utilizes bagasse and straw, has the potential to further enhance the value of Brazilian ethanol. This technology is particularly attractive to markets that prioritize biofuels derived from waste materials, as it can provide feedstock with minimal environmental impact.

In the national market, the production of anhydrous and hydrated ethanol has fluctuated over the past six years (Figure 3). Initially, there was an increase in production following the implementation of the RenovaBio policy (from the 2018/19 to 2019/20 harvests). However, this upward trend was interrupted by a significant drop in energy consumption during the COVID-19 pandemic, which lasted from March 11, 2020, to May 5, 2023, according to the World Health Organization (https://www.who.int/europe/emergencies/situations/covid-19). A recovery in the consumption of this biofuel became more evident during the 2022/23 harvest, with projections indicating an upward trend in the coming years. This resurgence is driven by a growing interest in renewable energy due to concerns about Climate Change and the ongoing support provided by the RenovaBio policy.

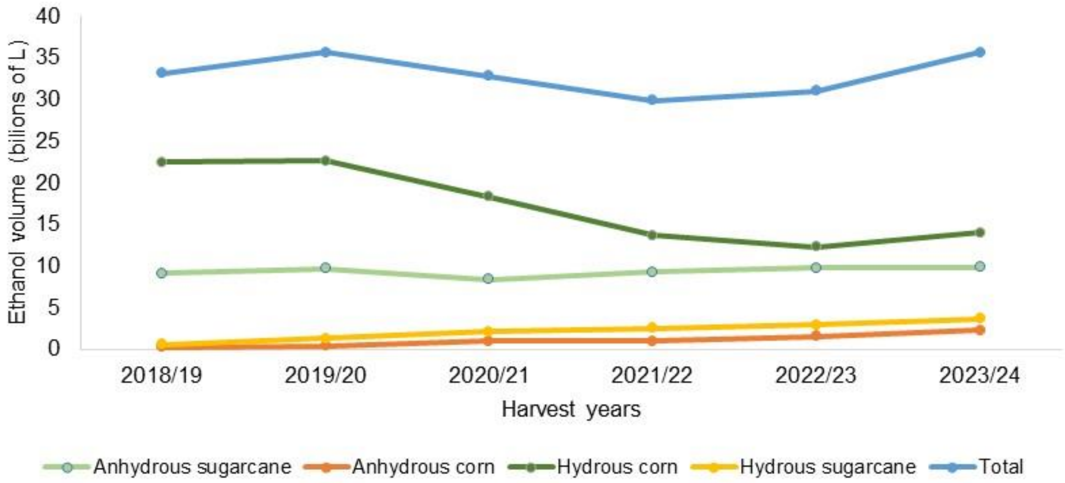

Figure 3. Evolution of sugarcane and corn ethanol production in Brazil. Source: Conab, 2023.

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Ethanol production from sugarcane remains the most traditional method of generating this biofuel in Brazil. However, recent years have seen a rise in the supply of corn ethanol (Figure 4). Despite this shift, sugarcane continues to dominate, contributing 83% of the national ethanol volume, underscoring its importance for national energy security. Notably, the increase in corn ethanol production has not diminished the availability of sugarcane ethanol (Figure 3). Instead, these two sources are complementary, particularly in states like Mato Grosso and Mato Grosso do Sul, where grain production is predominant.

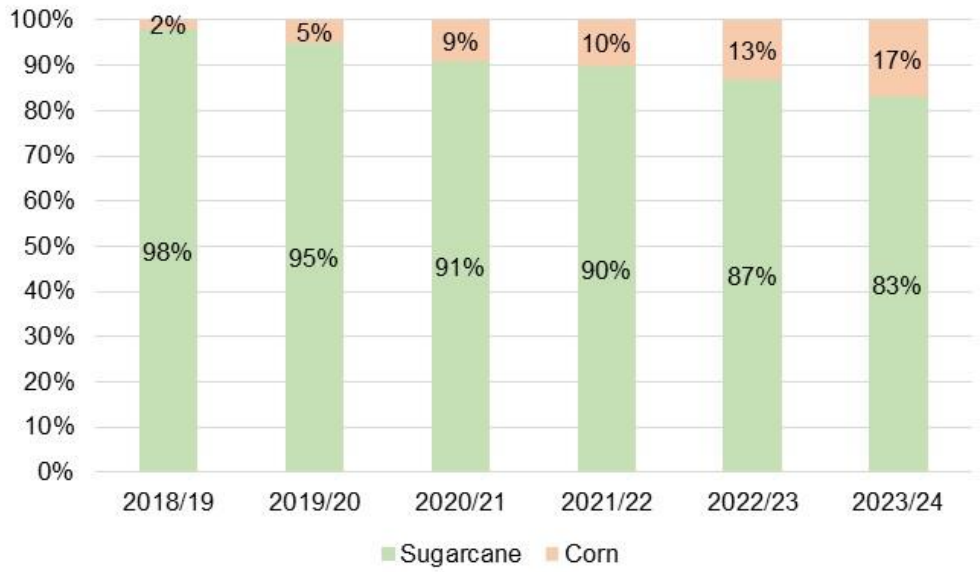

Figure 4. Percentage (%) of participation of sugarcane and corn ethanol in national ethanol production covering the harvests from 2018/2019 to 2023/2024 (Conab, 2023).

Currently, there are 331 ethanol production units authorized by the ANP operating in Brazil. Among these, units using sugarcane stalks as raw material, known as first-generation (1G) units, include distilleries (producing only ethanol), mills (producing both sugar and ethanol), and “flex” units (producing ethanol from both sugarcane and corn) distributed throughout Brazil. Additionally, some units employ second-generation (2G) technology to produce ethanol from lignocellulosic materials, specifically bioethanol derived from sugarcane bagasse and straw. There are also facilities dedicated exclusively to the production of corn ethanol.

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The RenovaBio policy establishes specific pathways for all types of ethanol, incorporating individualized data declaration structures (Brazil, 2017). For first-generation (1G) ethanol (both hydrated and anhydrous) derived exclusively from sugarcane, there are 268 units certified by RenovaBio. Additionally, there are four 1GFlex units that use "primary" data for the industrial stage and "primary" or "default" data for the agricultural stage (Figure 5). Notably, these units have collectively obtained 107.8 million CBIOs between 2020 and 2024, representing the same value in tons of CO_2eq of avoided emissions, as recognized within the policy.

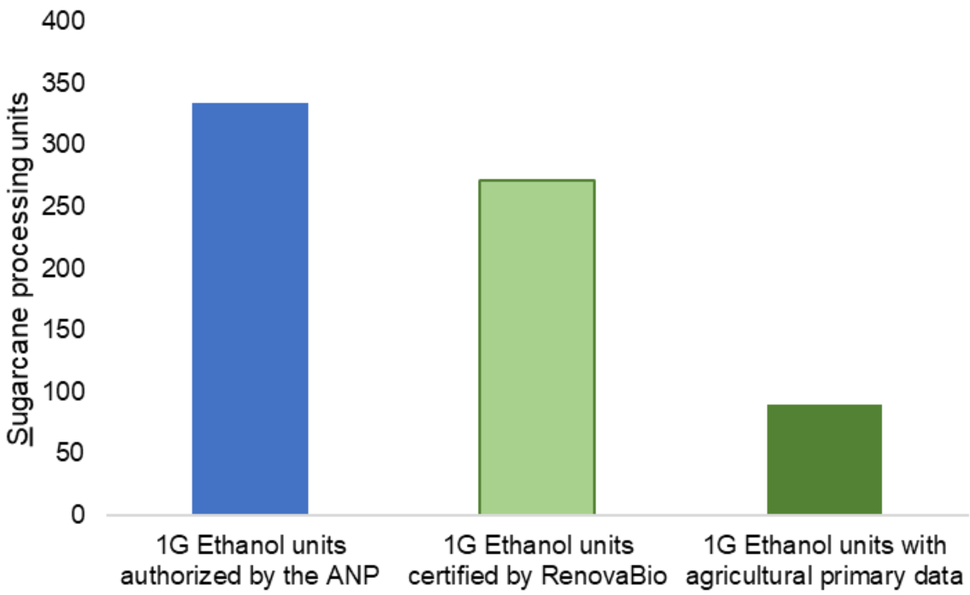

Figure 5. Plants producing sugarcane ethanol with first generation technology (1G), authorized by the ANP; certified by RenovaBio; and offering “primary data” (source: ANP, 2024).

To enable the option to input “default” data (“typical + penalty”) for sugarcane in RenovaCalc, it was necessary to identify the “typical” agricultural production profile of Brazilian sugarcane. The first “typical” profile was established in 2017, coinciding with the construction of RenovaCalc and the onset of RenovaBio regulations. This profile was based on information from the Brazilian sugarcane production inventory published in ecoinvent 3.1, which was the most current

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version available at the time. Ecoinvent is a leading international database of Life Cycle Inventories (LCI). The inventory used was the “market for sugarcane BR”.

The LCI “market for sugarcane BR” was constructed based on the most common agricultural input consumption profiles and agricultural operations in sugarcane production, from the 2012-2014 harvests, in six Brazilian states (São Paulo, Paraná, Minas Gerais, Goiás, Mato Grosso do Sul and Mato Grosso). These states collectively represented 80% of the total sugarcane stalks produced in the country (Figure 6). The data collection was conducted under the “Life Cycle Inventories of Brazilian agricultural products: a contribution to the ecoinvent database – ICVAgroBR” project (Folegatti-Matsuura and Picoli, 2018), a partnership between Embrapa Environment and the National Laboratory of Biorenewables (LNBR). National statistical databases were used (IBGE - Brazilian Institute of Geography and Statistics; Conab – National Supply Company) and articles from scientific literature, as well as consultation with experts in the sugarcane field. The GT-ACV RenovaBio group processed the data and estimated emissions, following the protocols and guidelines of Nemecek and Schnetzer (2011) and the IPCC (2006).

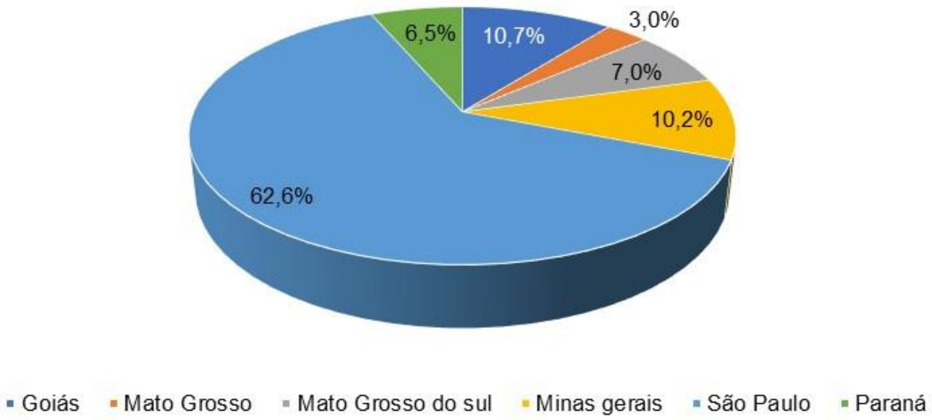

Figure 6. Participation of the main producing states in the “typical” sugarcane production profile in Brazil, used in RenovaCalc 7.0.

The parameters that describe the “typical” sugarcane production system, derived from the LCI “market for sugarcane BR” and adopted in ANP Resolution No. 758, are detailed in Chart 1. This system represents conventional sugarcane

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production without crop rotation or succession. The concept of an "average hectare of production" is included, encompassing the entire sugarcane production cycle. This includes operations and agricultural input consumption during field renovation and implementation, cane-plant production (12 and 18 months), and ratoon production, all weighted by the time each stage occupies the area. The total number of harvests considered is five.

Stalk productivity received a discount from the volume of seedling stalks used to implement the crop (Folegatti-Matsuura and Picoli, 2018). The inputs were broken down by the most used sources in Brazilian production, at the time, using urea, single superphosphate and potassium chloride to represent N-P_2O_5-K_2O fertilizers. Emissions related to the consumption of pesticides were determined from the sum of the mass of active ingredients applied, combined with the carbon footprint of these pesticides until use in the field, represented by the "unspecified pesticide" life cycle inventory. Regarding the use of fossil fuels, diesel consumption was estimated based on the declaration of use of machines and implements in different agricultural operations.

Chart 1. Values of the main sugarcane production parameters, which represent the "typical" condition for Brazil (2012-2014 harvests), according to the Life Cycle Inventory (LCI) "market for sugarcane BR" (ecoinvent, version 3.6).

Parameters	BR EI	General description
System	CV	Sugarcane produced in conventional cultivation (CV), considering a cycle of 5 cuttings, with the stages of reforming, cane-plant and sugarcane.
Productivity (kg/ha)	68.67	TSH – tons of stalks per hectare, considering the modeling of the "average hectare of production" and the discount for seedling stalks.
Limestone (kg/ha/year)	398	Limestone calculated from the application of around 1990 kg during the reform period, extrapolated to the average hectare.
Agricultural gypsum (kg/ha/year)	192	Gypsum calculated from the application of around 960 kg during the renovation period, extrapolated to the average hectare.
N (kg/ha)	76	Nitrogen, using urea as the predominant source, with doses obtained for the main producing states.
P_2O_5 (kg/ha)	30	P_2O_5, using Single Superphosphate as the predominant source, with doses obtained for the main producing states.
K_2O (kg/ha)	93	K_2O, using Potassium Chloride as the predominant source, with doses obtained for the main producing states.
Vinasse (mm)	3	Volume of vinasse, with a concentration of 0.38% N.
Filter cake (t/ha)	2.1	Quantity of filter cake (wet basis), with a concentration of 2.8% N.
Ash (kg/ha)	494	Amount of ash.
Diesel B10 (L/ha)	218	Diesel calculated from operations used in the main producing states.

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Table 1 shows the efficiency indices used in Resolution No. 758 (ANP, 2018) to represent the "typical" profile of Brazilian sugarcane on a national scale. The calculation was based on Chart 1, using each parameter divided by the national productivity of the period.

Table 1. "Typical" profile and default profile of sugarcane production used in RenovaCalc (up to version 7.0).

Parameter	"Typical" Profile	"Default" Profile
Burned area (%)	18	100
Calcitic or dolomitic limestone (kg/t sugarcane)	5.79	12.00
Agricultural gypsum (kg/t sugarcane)	2.79	5.00
Synthetic nitrogen fertilizers (kg N/t sugarcane)	1.11	2.00
Synthetic phosphate fertilizers (kg P_2O_5/t sugarcane)	0.44	1.00
Potassium synthetic fertilizers (kg K_2O/t sugarcane)	1.35	2.00
Organic nitrogen fertilizers – Vinasse (L/t sugarcane)	440.2	1000
Nitrogen concentration in vinasse (g N/L)	0.38	0.38
Organic nitrogen fertilizers – Filter cake (kg/t sugarcane)	30.6	42.8
Nitrogen concentration in filter cake (g N/kg)	2.80	2.80
Organic nitrogen fertilizers – Ash (kg/t sugarcane)	7.2	10.1
B10 diesel fuel* (L/t of sugarcane)	3.18	6.00

Source: Matsuura et al. (2018).

*In ANP Resolution 758/2018, the B8 mixture is mentioned, but after updating RenovaCalc 7.0, B12 has been used.

After determining the "typical" profile, penalties were established to compose the "default" profile. In this action, the upper limit was considered of the values observed in the field for each parameter, through consultation with experts and in discussions within the GT-ACV RenovaBio, valuing a conservative approach.

Sugarcane emissions calculated in RenovaCalc 7.0 (updated on 12/22/2020), using the condition of average productivity of 68.67 t/ha of stalks in an area of 100 ha, was 33.48 and 65.10 kg of CO_2eq/t of sugarcane stalks, respectively for the "typical" and "default" profiles. In this simulation, the "default" profile had emissions 2.2 times higher than the "typical" profile.

1.3. Regionalization of the sugarcane agricultural production profile

RenovaCalc has sufficient sensitivity to discriminate between different production profiles in both the agricultural and industrial stages of biofuel

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production. This capability allows users to reliably represent their biomass production methods, including the evolution of production systems, using "primary data". However, the "default" option of the agricultural stage, as it is a generic alternative for data representation, lacks sensitivity to changes in production profiles across different regions and their technological advancements.

After five years of successful implementation of the RenovaBio policy, it has become clear that representing "default" data should account for the regional differences in sugarcane production across the country. This approach aligns with the Policy's fundamental premise of differentiating and rewarding producers based on their energy-environmental performance and continues to encourage the use of "primary data" in all stages of biofuel production.

The challenges of representing production systems in the different regions of a continental country such as Brazil are significant, due to the scarcity of public information with complete technical parameters for sugarcane production. One of the possible sources of data, in addition to technical-scientific literature, is RenovaCalc itself, based on the primary database filled in by feedstock producers, which in the case of sugarcane is viable due to the high number of "primary data" declarants, who are certified by firms authorized by the ANP. Thus, they constitute a robust database of certified parameters, which favors the representation of culture, unlike other raw materials.

Thus, the present study aims to characterize "typical" sugarcane production systems, considering the reality of the different Brazilian producing regions which, after suffering penalties, can be used in the "regionalized default" data option in RenovaCalc.

2. Material and Methods

The study was carried out by Embrapa Environment with support from the ANP, the LNBR and the production sector. Two RenovaBio principles were respected:

i) <u>Encouraging the use of "primary" data in RenovaCalc</u>

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Since "primary" data best represents the technology adopted by producers for both biomass and biofuel production, the policy encourages its use at all stages of the biofuel's life cycle. Recognizing the superior quality of this data, we have chosen to use the "primary data" declared in the certifications conducted up to 2023 under RenovaBio for this update.

ii) Transparency in the methodology and parameters used in RenovaCalc

The construction and updating of RenovaBio's regulations are based on consultations and effective participation of the productive sector, including unrestricted access to data and calculations used in RenovaCalc.

2.1. Composition of the sugarcane production profile

The state scale was selected as the smallest unit for regionalization, thus avoiding violating the principle of *Incentive to the use of "primary" data in RenovaCalc*, adopted in RenovaBio (ANP, 2018). Figure 7 shows the simplified scheme of the strategy for constructing the "typical" sugarcane production profile for each of the Brazilian states.

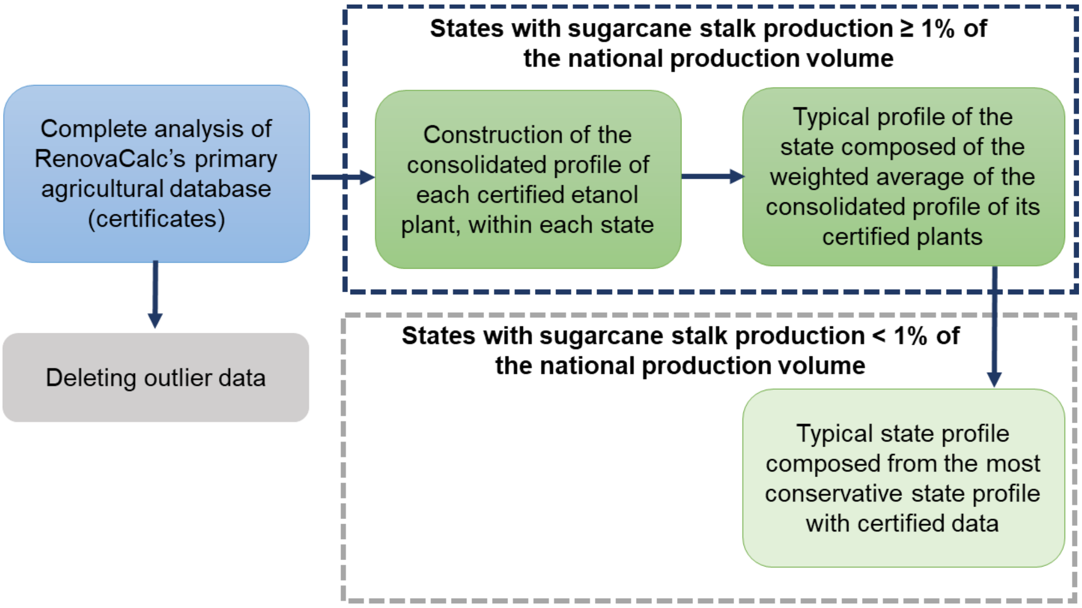

Figure 7. Composition of "typical" state sugarcane profiles in Brazil, based on primary agricultural data declared in certifications carried out at RenovaBio.

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The following represent the criteria adopted to guarantee the representation of the different technologies used in sugarcane production regions in the country, using certified data from processes of seven (7) inspection companies accredited by the ANP:

a) Analysis of the contribution of sugarcane stalk production by each Brazilian state to the national total. This analysis utilizes the statistical data from the Brazilian Institute of Geography and Statistics (IBGE) for the harvests of 2019, 2020, and 2021 (IBGE, 2023).

b) Compilation of primary sugarcane data from RenovaCalc, supplemented with data provided by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP). This also includes research from international agricultural production databases such as the ecoinvent database and the Global Feed LCA Institute (GFLI) database. Additionally, information from Embrapa, IBGE, and the National Supply Company (Conab) statistical database was utilized.

c) Characterization of the "typical" sugarcane production system in Brazilian states where stalk production is ≥ 1% of the national volume. For other states, a "generic and conservative" profile is used, particularly concerning greenhouse gas (GHG) emissions.

d) Use of "primary" agricultural data extracted from RenovaCalc for ten Brazilian states, with ethanol producing units certified by seven ANP authorized inspection firms, between 2018-2022. Data available for states that had stalk production < 1% of the national production volume were also considered.

e) Analysis of the representativeness of "primary" sugarcane agricultural data extracted from RenovaCalc, in relation to state stalk production.

f) Detailed analysis of the parameters declared in RenovaCalc (and certificates), excluding data considered atypical (errors in the positioning of commas and periods, number of decimal places, duplicate values and "outliers").

g) Construction of the consolidated profile (weighted average) of certified "primary" agricultural data, considering all technical parameters present in RenovaCalc, declared by each of the sugarcane ethanol producing units, in all certified years and in the states where are located. In this way, each sugarcane

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ethanol producing unit had a consolidated profile per declared year, within each state.

h) Proposition of the "typical" state profile based on the weighted average of the consolidated profiles of the producing units that are part of that state.

2.2. Validation of regionalized sugarcane production profiles

The validation of the technical parameters that made up the "typical" profiles of each Brazilian state was carried out through: a) consultation with experts in sugarcane cultivation and members of the GT-ACV RenovaBio; b) presentation of data in an online workshop, with the participation of representatives from the production sector; and c) presentation of data in a technical report, made available to the production sector for analysis and feedback with duly justified suggestions, with a technical-scientific basis and following the premises of the study.

2.3. Determination of carbon intensity (CI) in RenovaCalc

The calculation of the carbon intensity (in kg of CO_{2eq}/t of sugarcane stalks) of the "typical" profile for the different Brazilian states was carried out directly in RenovaCalc, in version 7.0 (effective in 2023) and in version 9.0, which will be implemented soon. For this, the previously calculated efficiency indices were used in a simulation, considering an area of 100 ha and production derived from productivity.

RenovaCalc version 9.0 received a series of updates compared to the previous version, as described below:

- Use of version 3.9.1 of the ecoinvent database to calculate the carbon footprints of sugarcane production inputs.
- Use of "market type datasets", whenever available, considering the geographical scope preferably BR (Brazil), RoW (rest-of-world) or GLO (Global).
- Calculation of the Carbon Footprint of inputs using the SimaPro software (version 9.5.0.0), using GWP 100 (IPCC, 2021), without accounting for infrastructure and emissions from land use change (MUT).

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- Update of characterization factors, in accordance with AR6 (IPCC, 2019).
- Update of emission factors for mineral, organic fertilizers and cultural waste according to the IPCC (2019).
- Update of the value of the “agricultural residue ratio on soil” based on the IPCC (2019).

3. Results and Discussion

3.1. Representativeness of Brazilian states in sugarcane production and selection of the database to compose their “typical profiles”

In Brazil, eight states were identified as having sugarcane stalk production of ≥1% relative to national production during the 2019, 2020, and 2021 harvests (IBGE, 2023). Collectively, these states represented 99.6% of the total production in the country (Figure 8). This indicates that the study should propose "typical" sugarcane production profiles for each of these states. São Paulo (SP) stood out as the largest producer, contributing 57% of the national production. Other states with significant production included Goiás, Minas Gerais, Mato Grosso do Sul, Paraná, and others.

The considerable distribution of sugarcane production across several states and Brazil's prominent role in global stalk production, being historically ranked first by FAOSTAT, underscores the necessity for a robust and recognized database to characterize regional production systems. Consequently, the use of RenovaCalc's primary agricultural database was prioritized. Consultations were also made with two international product life cycle inventory databases—the ecoinvent database and the Global Feed LCA Institute (GFLI) database. However, these inventories only represented six Brazilian states (SP, GO, MG, MS, PR, and MT) and included input consumption and agricultural operations data from the 2014 harvest, making them outdated compared to RenovaCalc data. This reinforces that using certified data from RenovaBio is the most appropriate option.

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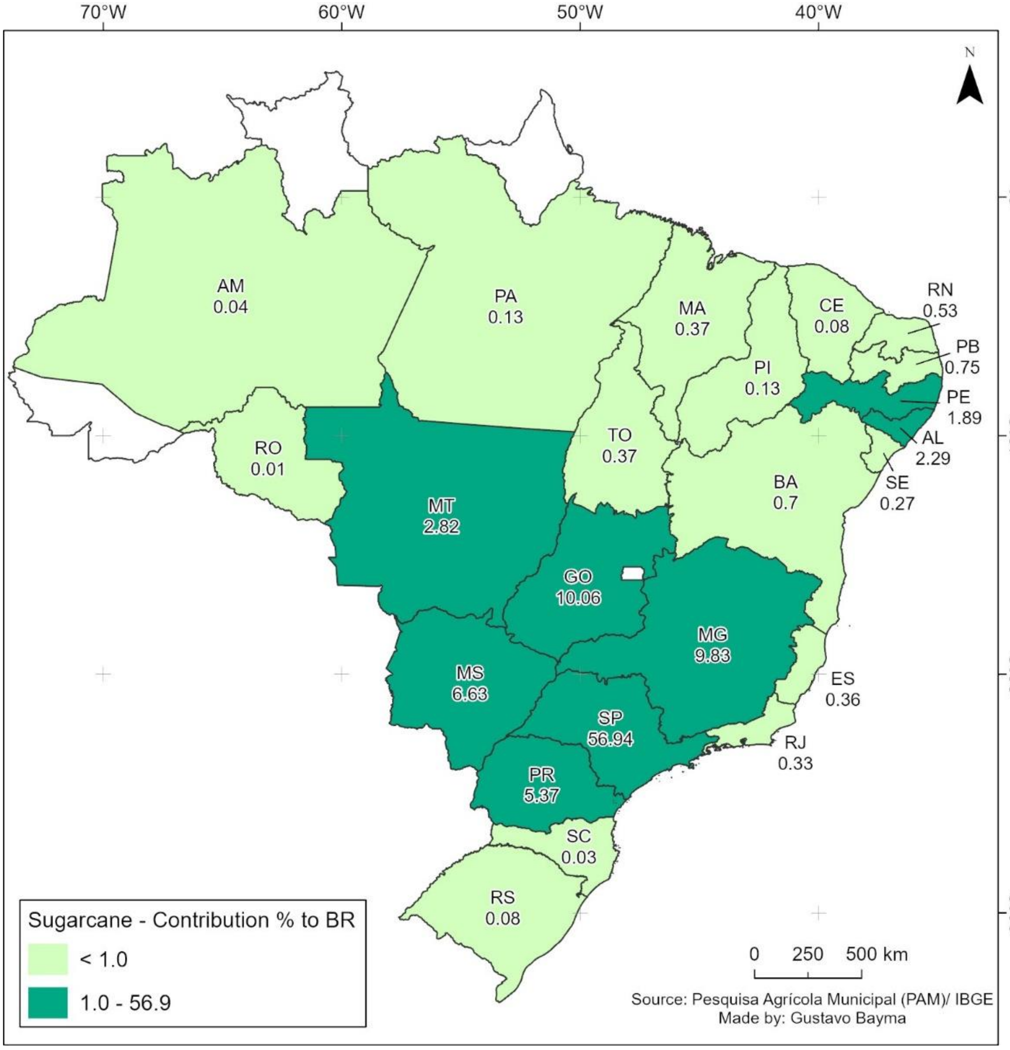

Figure 8. Sugarcane producing states and their percentage contributions to the production of the crop in Brazil, considering the IBGE years 2019, 2020 and 2021.

In the analysis of RenovaCalc's primary agricultural database, the availability of a large number of records was verified, even with the exclusion of atypical data, in different years of certification, being: 21 records in 2018, 201 records in 2019, 588 records in 2020, 551 records in 2021 and 32 records in 2022. This robust mass of certified data was considered adequate for characterizing the sugarcane production system for ten Brazilian states (SP, GO, MG, MS, PR, MT, AL, PE, PB and BA), contributing both to the eight largest producers (Figure 8), and to two additional states, PB and BA.

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The representativeness of the information from the primary agricultural database certified in RenovaBio, used for extrapolating state profiles, is illustrated in Figure 9. For the seven most relevant states, it was found that the contribution of certified sugarcane accounted for more than 10% of the total stalks produced in each respective state during the study period. The highest contributions were observed in Goiás (GO), Minas Gerais (MG), and São Paulo (SP), which together comprised over 77% of the national sugarcane production during this period. This validated the selection of this data set and ensured its reliability in representing the most current production profile of the crop at the state level. Additionally, it is important to note that since its inception, the RenovaBio policy has envisioned the RenovaCalc database providing essential feedback for its optimization and continuity.

3.2. Composition of the "typical" profile of sugarcane production on a state scale

The "typical" profile of sugarcane production, for the ten Brazilian states that have primary agricultural data certified by RenovaBio, received a specific change, identified as necessary by experts. Adjustments were made to the nitrogen and phosphorus doses for the MAP and DAP sources, so that the N and P_2O_5 concentrations of the formulations were aligned based on the N content and, for cases where the adjustments increased the amount of P_2O_5, the surplus was discounted in the category – "Other P_2O_5 fertilizers".

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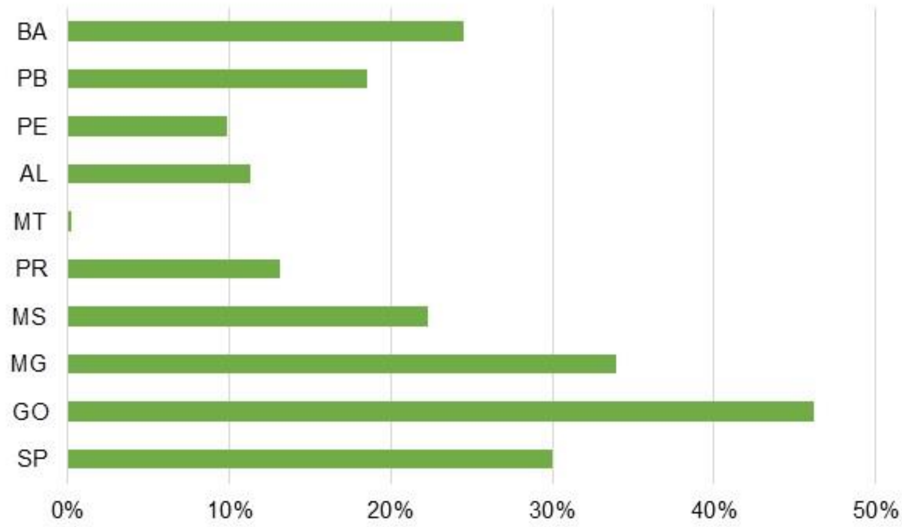

Figure 9. Percentage of contribution from sugarcane stalk production with "primary data", declared in RenovaCalc, in relation to state stalk production from the 2019-2020-2021/IBGE harvests.

Table 2 illustrates the comparison of "typical" state profiles with the typical profile on a national scale, in ANP Resolution 758 (ANP, 2018). There were a series of improvements in the description of the production profile, for example, with more current and specific data on plant impurities coming from the field - information that affects the final carbon intensity of the crop, as it changes the real calculation mass.

Another significant improvement was updating the fraction of burned area relative to the total cultivated area. The updated values for the largest producing states ranged between 1.8% and 5.3%, significantly lower than the 18% used in the national scale of ANP Resolution 758. In contrast, states in the northeast of Brazil, where burning is still practiced, reported rates between 52% and 86%. This parameter substantially impacts the carbon intensity of sugarcane production.

There was also better discrimination of doses and sources of limestone and nitrogen, phosphate and potassium fertilizers, which in the national profile was restricted to dolomitic limestone, urea, single superphosphate and potassium chloride. This enabled updating consumption values while using more accurate life cycle inventories for the production of these inputs. In the case of limestone,

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it was also possible to adjust emissions in the field, using different factors for each source, following the IPCC guide (2019).

Limestone volumes were predominantly adjusted upwards, reflecting the sugarcane sector's enhanced emphasis on liming to boost productivity. The use of synthetic nitrogen fertilizers aligned closely with the values prescribed by ANP Resolution 758, except for Bahia, which reported higher doses. Conversely, the application of phosphate fertilizers nearly doubled compared to previous values, while the use of potassium fertilizers decreased. This reduction in mineral potassium usage likely results from the increased volume of vinasse application observed across all states.

The use of organic fertilizers saw a significant increase across the states. In addition to the increased use of vinasse, there was also a rise in the reported use of higher doses of filter cake and other organic products. This trend towards valuing organic inputs is growing in Brazilian agriculture overall. Specifically, in the sugarcane sector, the practice of reusing agro-industrial residues is already well-established, and the collected data indicate that this practice is intensifying.

Regarding fuels used in agricultural production, it was found that the regionalization of profiles allowed for greater differentiation between energy sources, which was previously concentrated on diesel. Consumptions for diesel, gasoline, ethanol, electricity from the grid, as well as solar energy were characterized. Regarding diesel, better discrimination concerning the biodiesel content in the mixture was also possible.

A limiting point that deserves attention in future updates was the lack of information regarding the consumption of pesticides (herbicides, insecticides, fungicides, nematicides, among others). This is because RenovaCalc does not request this type of input (as it does not have a significant impact on the carbon intensity of the final product), making it impossible to retrieve this information through the tool.

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3.3. Carbon intensities - CI

The carbon intensities (CI) relative to the state profiles, simulated in RenovaCalc version 7.0 (RN 7.0, in use) and 9.0 (RN 9.0, to be implemented), are shown in Figure 10. The simulation in RN 7.0 resulted in CI between 34.5 and 46.7 kg of CO_2eq/t of sugarcane stalks, while in RN 9.0 the values were 36.9 to 53.5 kg of CO_2eq/t of sugarcane stalks. The values calculated in the version to be implemented (RN 9.0) are on average 10% higher than those in the current version, due to the updates described in the methodology. Looking only at the "typical" value found in Resolution 758 (BR 758) in Figure 10, it appears that this update contributed with around a 3% increase in average carbon intensity, with greater weight in production profiles on a state scale.

Comparing the carbon intensities for each state reveals an increase relative to the "typical" reference profile outlined in Resolution 758 for all states studied, in both versions of RenovaCalc. This increase is not due to regionalization itself but to updates in input consumption, a more detailed accounting of corrective and fertilizer sources, and the inclusion of various energy sources not previously covered in the national profile. It should be noted that the regionalized values will still be augmented by a "penalty" to form the "default" regionalized profile in RenovaCalc.

Differences in sugarcane carbon intensity (CI) between states resulted from varying burning rates and differences in input consumption. Notably, the reduction in the percentage of sugarcane burning for harvesting in the main producing states, now between 1.8% and 5.3%, compared to the previous value of 18%, demonstrates a more accurate representation of this practice across different regions of Brazil.

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Table 2. "Typical" efficiency indices for sugarcane cultivation in different states in Brazil.

Agricultural inputs	SP	GO	MG	MS	PR	MT	AL	FOOT	PB	BA	Others	RANP/758
Vegetable impurity (kg/t sugarcane)	75.93	73.80	75.31	77.03	70.28	53.10	54.59	71.00	72.79	58.20	72.79	-
Straw collected (%)	0.000265	0.001134	-	0.000356	-	-	-	-	-	-	-	-
Burned area (%)	4.84	4.20	5.29	1.80	2.82	-	77.44	86.20	62.20	52.12	62.20	18.00
Limestone												
Calcitic (kg/t sugarcane)	0.30	0.17	0.92	0.11	-	-	-	0.01	0.42	-	0.42	0.00
Dolomitic (kg/t sugarcane)	11.57	8.76	12.11	14.85	13.40	12.65	11.20	10.85	9.19	0.00	9.19	5.79
Gypsum (kg/t sugarcane)	5.37	3.63	6.09	4.36	5.07	5.77	2.11	0.16	0.92	1.85	0.92	2.79
Nitrogen												
N Urea (kg/t sugarcane)	0.35	0.25	0.20	0.39	0.32	-	0.07	0.05	0.06	1.14	0.06	1.11
N MAP (kg/t sugarcane)	0.09	0.09	0.09	0.08	0.02	0.10	0.04	0.08	0.06	0.05	0.06	-
N DAP (kg/t sugarcane)	0.0004	-	0.0071	0.0019	-	-	0.02074	-	0.0158	-	0.0158	-
N Ammonium Nitrate (kg/t sugarcane)	0.34	0.34	0.36	0.23	0.16	0.84	0.43	0.02	0.30	0.21	0.30	-
N UAN (kg/t sugarcane)	0.09	-	0.01	-	-	-	-	-	-	-	-	-
N Anhydrous Ammonia (kg/t sugarcane)	0.004	-	-	-	-	-	-	-	-	-	-	-
N Ammonium Sulfate (kg/t sugarcane)	0.01	0.11	0.06	0.09	0.01	0.05	0.43	0.93	0.25	0.04	0.25	-
N Calcium Nitrate (kg/t sugarcane)	0.0001	0.002	0.0003	0.007	-	-	0.006	0.001	-	0.376	-	-
N others (kg/t sugarcane)	0.12	0.11	0.27	0.35	0.35	0.09	0.23	0.01	0.43	-	0.43	-
Phosphorus												
P_2O_5 MAP (kg/t sugarcane)	0.41	0.46	0.50	0.41	0.13	0.53	0.22	0.40	0.32	0.25	0.32	-
P_2O_5 DAP (kg/t sugarcane)	0.001	-	0.02	0.005	-	-	0.06	-	0.04	-	0.04	-
P_2O_5 SSP (kg/t sugarcane)	0.03	0.01	0.02	0.01	0.004	0.11	0.02	0.02	-	-	-	0.44
P_2O_5 STP (kg/t sugarcane)	0.019	0.035	0.013	0.023	0.029	-	-	-	-	-	-	-
P_2O_5 Others (kg/t sugarcane)	0.14	0.06	0.14	0.41	0.42	-	0.10	-	0.03	0.01	0.03	-
Potassium												
K_2O KCL (kg/t sugarcane)	0.66	0.74	0.67	0.78	0.23	0.69	1.15	1.49	1.10	0.76	1.10	1.35
K_2O Others (kg/t sugarcane)	0.12	0.10	0.27	0.08	0.59	0.11	0.23	0.01	0.34	0.42	0.34	-
Vinasse (L/t sugarcane)	663.3	700.8	699.5	625.8	378.0	1,220.7	595.3	1,201.2	1,935.3	16,587.8	1,935.3	440.0
Conc. N (g/L)	0.38	0.37	0.34	0.34	0.98	0.19	0.30	0.34	0.33	0.02	0.33	0.38
Filter cake (kg/t sugarcane)	32.56	21.64	27.32	8.16	22.11	96.47	26.48	22.40	29.00	14.81	29.00	30.60
Conc. N (g/kg)	2.92	2.60	2.87	3.16	2.28	2.80	2.71	2.80	2.80	2.80	2.80	2.80
Ash (kg/t sugarcane)	13.47	9.97	6.64	5.94	14.89	-	1.47	18.35	8.87	-	8.87	7.20
Other organics (kg/t sugarcane)	4.63	1.21	6.21	18.10	6.44	-	-	-	-	27.66	-	-
Diesel												
B10 (L/t sugarcane)	1.84	1.80	2.15	2.18	2.31	3.96	1.45	1.77	1.83	1.89	1.83	3.18
B11 (L/t sugarcane)	1.08	0.91	0.63	0.53	0.68	-	1.21	1.16	1.21	0.16	1.21	-
Bx (12%) (L/t sugarcane)	1.31	1.22	1.55	1.30	1.51	-	0.98	1.08	1.01	0.90	1.01	
Gasoline (C) (L/t sugarcane)	0.004	0.003	0.006	0.004	0.001	-	0.035	0.042	0.038	0.013	0.038	-
Hydrated ethanol (L/t sugarcane)	0.22	0.41	0.22	0.12	0.20	0.33	0.40	0.08	0.26	0.18	0.26	-
Electricity Mix (kwh/t sugarcane)	0.04	0.57	0.14	-	-	-	0.89	0.16	7.98	23.09	7.98	-
Solar electricity (kWh/t sugarcane)	0.0002	-	-	-	-	-	-	-	-	-	-	

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PB was the state whose sugarcane presented the highest CI, in the simulation using version 9.0 of RenovaCalc (Figure 10), due to the greater consumption of inputs, in relation to the “typical” profile of Resolution 758 (Table 1). In version 7.0 of RenovaCalc, the sugarcane with the highest carbon intensity was from BA. The states of GO and SP presented production profiles with lower carbon intensities, showing a more sustainable technological standard, which is very positive, considering that they are the largest national producing states (Figure 9).

The largest CI of sugarcane produced in the state of PB, with emissions of 45.5 kg CO_2eq/t (in version 7.0 of RenovaCalc) and 53.5 kg CO_2eq/t of sugarcane (in version 9.0), led to deciding it to represent the other states, which do not have their own production profile, due to a conservative approach.

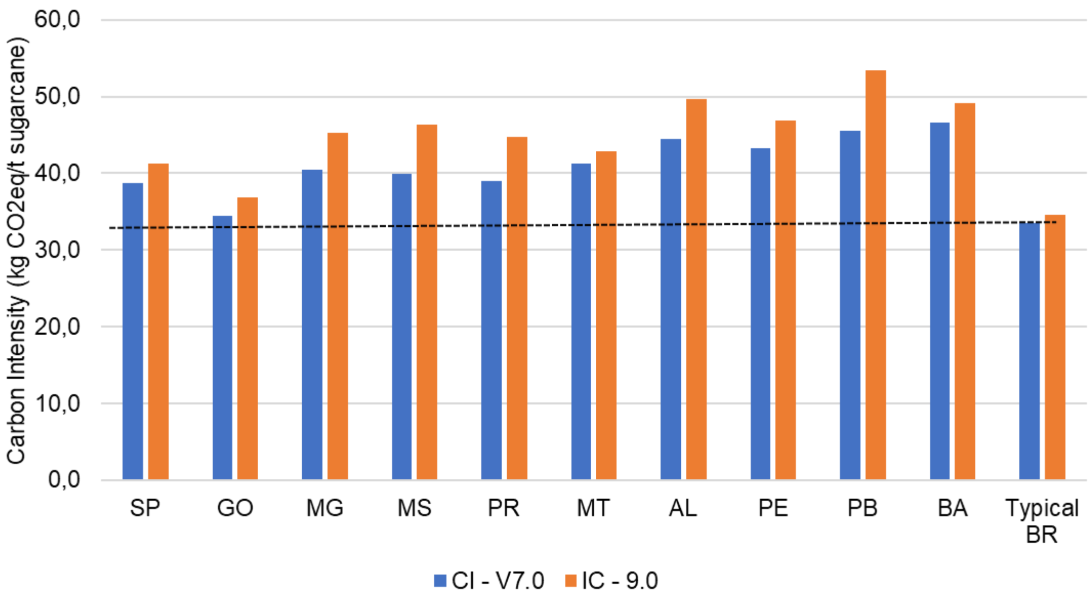

Figure 10. Carbon intensity of sugarcane produced in a “typical” production system for each Brazilian state and the reference profile contained in ANP Resolution 758 (ANP, 2018), calculated in versions 7.0 and 9.0 of RenovaCalc.

4. Final remarks

The "typical" sugarcane production profile differs from the "default" profile used in RenovaCalc. The "default" profile includes the "typical" profile with an

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added penalty to ensure that emissions from biomass production are not underestimated for producers who cannot provide “primary data” and whose biofuel is part of the certification process under this Policy.

The proposal to regionalize the "typical" sugarcane production profiles at the state level aligns with RenovaBio's principles, which continuously encourage the use of “primary data” at all stages of biofuel production. Leveraging information from the RenovaBio certification database enhances the Policy's transparency and credibility. Additionally, the timeliness of the data (2018-2023) improves the representation of technologies and innovations adopted in the sector.

The variation in carbon intensity of sugarcane across different states highlights the importance of utilizing state-specific sugarcane production profiles in RenovaCalc. The availability of "typical" profiles for the largest sugarcane-producing states in Brazil allows for a more accurate representation of local crop production. This approach supports establishing "default" data within RenovaCalc, replacing the national profile previously outlined in ANP Resolution 758/2018.

Regularly updating these profiles in alignment with other policy initiatives can enhance the representation of current production systems. However, determining the appropriate update interval requires consideration of broader issues, such as goal-setting, the validity of production unit certifications, and other related factors.

It is also recommended to seek updated information on pesticide use from additional databases, even if these input values do not significantly impact carbon intensity.

5. Conclusions

The updated "typical" sugarcane production profile, when considered at the state level, provides a more accurate representation of crop production conditions in Brazil. This enhanced profile is recommended for use in RenovaCalc, after incorporating the necessary adjustments to meet the data “default” requirements, thereby ensuring policy compliance.

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Utilizing sugarcane production efficiency indices derived from RenovaCalc's own 1GS and 1GFlex ethanol certifications ensures accuracy and credibility in representing the production profiles. These indices reflect the technologies and innovations adopted by the sugarcane sector during its participation in RenovaBio. It is advisable to maintain this update procedure at intervals consistent with other policy initiatives, adhering to the established principles.

6. Financing

This study was funded by Finep project 01.22.0591.00, SEG 10.23.00.039.00.00.

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