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Article

Carbon Footprint of Brazilian Agriculture Based on Field Operations

João P. S. Veiga [1], Gustavo V. Popin [2], Carlos E. P. Cerri [3] and Thiago L. Romanelli [4,*]

1 School of Agribusiness, UniFAJ/FAAGROH, Holambra 13825-000, SP, Brazil; jpsveiga@gmail.com
2 Graduate Program on Soil and Plant Nutrition, USP/ESALQ, Piracicaba 13418-900, SP, Brazil; gustavo.popin@usp.br
3 USP/Center for Carbon Research in Tropical Agriculture (CCARBON) and USP/ESALQ—Department of Soil Sciences, Piracicaba 13418-900, SP, Brazil; cepcerri@usp.br
4 Laboratory of Systemic Management and Sustainability, Department of Biosystems Engineering, USP/ESALQ, Av. Pádua Dias, 11 Cx. P. 09, Piracicaba 13418-900, SP, Brazil
* Correspondence: romanelli@usp.br

Abstract: Agriculture has historically relied on fossil fuels as the primary source of energy, leading to significant greenhouse gas (GHG) emissions and exacerbating climate change. Brazil, as the third-largest producer and exporter of agricultural goods globally, plays a pivotal role in the transformation towards more sustainable practices. To this end, we propose a methodology to estimate CO_2 equivalent (CO_2-eq) emissions in agriculture, leveraging previous research on energy use in 23 crops in Brazil. The methodology aims to facilitate the comparison of emissions across different crops and production systems. Indirect emissions account for 36% of the total, while direct emissions account for 64%. Most direct emissions are due to the consumption of fertilizers and pesticides. The average emission per mass of product was 749.53 kg $CO_{2\text{-eq}}$ Mg^{-1}, with cotton having the highest emissions and eucalyptus having the lowest emissions per product. The results highlight the importance of assessing GHG emissions from crops to identify emission reduction opportunities and promoting more sustainable agricultural practices. The study's findings can inform policy recommendations and contribute to the development of sustainable agriculture practices globally, ultimately leading to a more environmentally friendly and economically viable agricultural sector.

Keywords: GHG emissions; sustainable practices; climate change; production system

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1. Introduction

World energy demand doubled from 1979 to 2018, with fossil fuels providing an average of 82% of global demand during this period [1]. Fossil fuel combustion is a major source of greenhouse gas emissions, significantly contributing to the increase in GHG gases and climate change [2]. Since the industrial revolution, the average GHG concentration in the atmosphere has risen from around 280 ppm to 424 ppm in 2024 [3,4]. In 2021, fossil fuel combustion emitted approximately 34.2 Gt $CO_{2\text{-eq}}$ worldwide [5]. This situation requires transformation to achieve sustainable levels of GHG emissions and mitigate climate change impacts [6].

Agriculture, forestry, and other land use (AFOLU) is unique for GHG mitigation, as it can act as a carbon sink and help other sectors [7–9]. The Intergovernmental Panel on Climate Change (IPCC) reported that agriculture alone can contribute to net emissions reductions of around 3.5 Gt $CO_{2\text{-eq}}$ yr^{-1} [9]. However, estimating emissions is complex due to varying methodologies. Agriculture encompasses countless production systems varying in intensity, mechanization, size, techniques, chemical usage, and technology, leading to myriad combinations and yields.

Brazil is the third-largest producer and exporter of agricultural goods globally [10]. Despite the sector constituting only 5% of Brazil's total energy consumption [11], the agricultural sector significantly contributes to environmental concerns, accounting for 25%

of the country's CO_2 emissions, excluding Land Use Change [12]. The primary contributors include enteric fermentation, manure management, synthetic nitrogen fertilizers, crop residues, limestone, and diesel fuel for mechanized operations. This underscores how imperative it is for the implementation of sustainable practices and environmental considerations within Brazil's robust agricultural industry and why sustainable practices are imperative.

Considering the significant uncertainty regarding agricultural emissions [9,13], and the necessity to correlate energy consumption to CO_2 flow in agriculture systems, this study applied a standardized methodology to facilitate the comparison of $CO_{2\text{-eq}}$ emissions across various agricultural crops and production systems. The study was built upon the findings of a previous study quantifying the energy embodied in 23 main crops in Brazil [14] and proposes a methodology for estimating $CO_{2\text{-eq}}$ by accounting only for direct and indirect inputs that are directly related to the production of the crops, and by excluding transport and post-harvest activities. The assessment expresses emissions per unit of area of the crop produced, per unit of production per crop, as well as for main production categories such as starch, oil, and human food. The innovative aspect of this study lies in the utilization of existing information from agricultural operations, typically used for cost estimation, as a proxy for estimating $CO_{2\text{-eq}}$ emissions. The results of the evaluated crops will be compared with previous studies on carbon emissions to validate the efficacy of the proposed methodology. The study achieves an easy-to-use tool to measure different crop practices pointing at which are better considering $CO_{2\text{-eq}}$ emissions, which is a knowledge gap according to IPCC [9,13].

2. Materials and Methods

The scope of this analysis is based on the processes that happens on farms and does not take into account transport or post-harvest activities as shown on Figure 1.

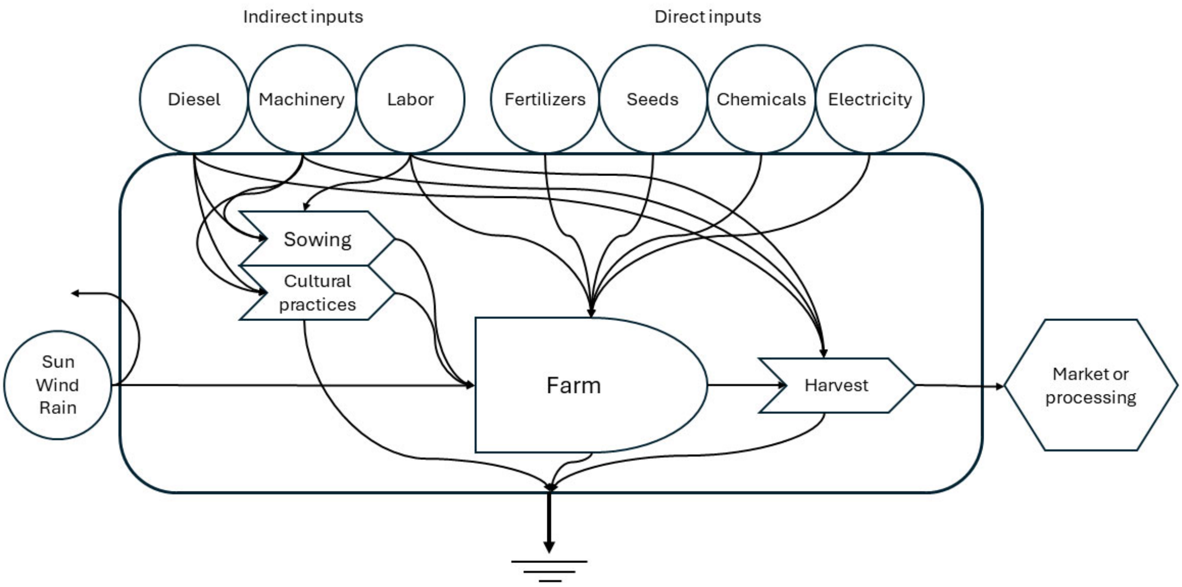

Figure 1. System boundaries, inputs, and processes considered.

By excluding transport and post-harvest activities, the study can focus on the emissions that are directly related to the production of the crops, making it easier to compare the emissions of different crops and production systems, as proposed in the scope of the study. However, in the final result of the product for consumption it is vital to consider these steps, which can be inserted in more detail from other studies that specifically consider these activities.

The total emissions from the 23 agricultural products in Brazil were estimated based on the sum of all the actions and materials used during the development and productive stage of the product multiplied by its respective emission factor (EF). To allow comparisons, total emissions were presented in (carbon dioxide) $CO_{2\text{-eq}}$ in relation to the quantity of starch, oil, cotton, and horticultural and perennial crops produced per hectare yearly.

Data about crop composition, production, and yield, to determine the Functional Unit of each crop, were obtained as previously described by Veiga et al. (2015) [14]. The area each crop occupies was obtained from the SIDRA/IBGE system [15] and EMBRAPA publications [16,17], and for crops with no data available on the area covered, it was estimated by the total production and the average yield considered (lettuce and cucumber); this information is summarized in Table 1.

Table 1. Yield and area of crops considered.

Group	Crop	Yield (Mg ha^{-1}) [14]	Area (10^3 ha)	Source
Starch	Bean	3.0	2715	[15]
Starch	Cassava	22.0	1197	[15]
Starch	Maize	8.8	21,284	[15]
Starch	Potato	30.0	118	[15]
Starch	Rice	2.7	1657	[15]
Starch	Wheat	2.7	3167	[15]
Oil	Castor bean	0.8–1.5	46	[15]
Oil	Palm	2.2	201	[15]
Oil	Peanut	3.1–4.2	221	[15]
Oil	Soybean	3.2–3.1	41,142	[15]
Oil	Sunflower	4.2	38	[15]
Food	Banana	40.0	460	[15]
Food	Bell Pepper	35.0	13	[16]
Food	Carrot	42.2	30	[17]
Food	Cucumber	44.0	5	Calculated
Food	Lettuce	22.4	30	Calculated
Food	Onion	44.0	49	[15]
Food	Tomato	85.0	55	[15]
Others	Cotton	4.0	1649	[15]
Others	Coffee	2.1	1875	[15]
Others	Sugarcane	78.0	9890	[15]
Others	Citrus	34.0	571	[15]
		Yield (m^3 ha^{-1})		
Others	Eucalyptus	290.5	5500	[18]

Considering the different functions of the various proven crops, they were grouped into different groups, including carbohydrate crops, oil production crops, food crops such as fruits and vegetables, and other crops of economic interest.

As the analysis considers average data obtained from field operations, regional variations are inherently integrated into the practices analyzed.

Emission Factor

The Emission Factors (EFs) of diesel and gasoline were calculated summing up the EFs from production and direct use (combustion). To do that, we considered the following compositions: diesel is comprised of 90% fossil fuel and 10% biodiesel [19], and gasoline of 73% fuel and 27% ethanol [20]. The production EFs were estimated by multiplying the energy index of each fuel (MJ liter^{-1}) by the respective EF (kg $CO_{2\text{-eq}}$ MJ^{-1}). Energy indexes were obtained from the Brazilian energy balance [11]; production emissions of biodiesel, ethanol, and fossil fuel (diesel and gasoline) were obtained from Cerri et al. (2017) [21], Pereira et al. (2019) [22], and the JEC Well-to-Tank report v5 [23], respectively. The use EFs were estimated by multiplying the greenhouse gases emitted during combustion of each fuel [24] by the 100-years global warming potential (GWP), i.e., 1, 28, and 273 for carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), respectively [25]. The diesel and gasoline numbers of direct and indirect emissions are available in Table 2.

Table 2. Diesel and gasoline direct and indirect emissions.

Input	Unit	kg $CO_{2\text{-eq}}$ [1]		
		Production [4]	Direct [5]	Total
Diesel [2]	Liter	0.66	2.65	3.30
Gasoline [3]	Liter	0.50	2.13	2.63

[1] The 100-years global warming potentials (GWPs) for methane (CH_4) and nitrous oxide (N_2O) are 25 and 298, respectively [26]. [2] Diesel is composed of 10% biodiesel (mainly soybean) and 90% diesel fuel [13]. [3] Gasoline is composed of 27% anhydrous alcohol and 73% gasoline fuel [13]. [4] The production factors for diesel and gasoline fuel were obtained in [16]. The production factors for biodiesel and anhydrous alcohol were obtained in [14,15], respectively. The net heating values were obtained in [9]. [5] Direct emissions from all components were obtained in [17].

To determine the EFs from fertilizers, animal manure (used as a nitrogen source), and lime, emissions were separated into direct and indirect production (kg $CO_{2\text{-eq}}$ kg^{-1} of nutrient or lime). The production EFs for nitrogen (N), phosphorus (P), and potassium (K) fertilizers and the market share of each fertilizer (per nutrient source) in South America were obtained from Kool et al. (2012) [27]. The production EFs for N, P, and K were estimated by a weighted arithmetic mean between the production EF among fertilizers in South America and the corresponding market share. The lime production EF was obtained from [28]. No direct or indirect emissions were considered for P and K fertilizers.

To determine the direct and indirect (volatilization and leaching) emissions related to N in fertilizers and animal manure, default values (Tier I) presented in the 2019 Refinement of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories were used [29]. Direct emissions were calculated by multiplying the amount of fertilizer or animal manure applied by the N concentration in each source and the EF for direct use. The N concentrations in fertilizers and animal manure were obtained from [30] and Smith et al. (2006) [31], respectively. The direct EF was determined considering the default value of a 0.01 EF for N_2O emissions from N added as a synthetic fertilizer, organic amendments, and mineralized from mineral soil, the conversion of N_2O-N to N_2O ($\times$1.5714), and to $CO_{2\text{-eq}}$ ($\times$273) [25,29]. For flood rice, an additional EF was calculated, multiplying the amount of N added to the soil by a factor of 0.004 N_2O emissions from N inputs in flooded rice. The direct EF for lime was calculated by multiplying the amount of lime applied times the EF factor of 0.458—the emission of CO_2 from lime application times the conversion of CO_2–C emissions into CO_2 (44/12) [28].

The indirect EFs for fertilizers were calculated by multiplying the fraction of N that volatilizes as NH_3 and NOx, i.e., 0.15, 0.08, 0.01, and 0.05 for urea, ammonium, nitrate, and ammonium–nitrate-based, respectively, and the EF related to N_2O emissions for the atmospheric deposition of N on soils—a default value of 0.01 [29]. The EF for volatilization was determined with a weighted arithmetic mean between the EF from each synthetic fertilizer and its market share. The EF from leaching and runoff was quantified by multiplying the fraction of N lost through leaching and/or runoff in managed fields, i.e., 0.24 (default), and the EF related to N_2O emissions from N leaching and runoff, 0.011 [29]. The indirect EF for manure was determined in the same way as for synthetic fertilizers but using different values of the fraction and EF for volatilization and leaching. For volatilization, the respective default values for the fraction and EF were 0.21 and 0.01. To determine the EF of leaching and/or runoff, the values used were 0.24 and 0.011, respectively [29].

Emissions regarding the use of chemical products were calculated using the quantity and the pesticide production EF derived from Audsley et al. (2009) [32] and FAO (2017) [33]. The authors identified average energy inputs equal to 423 MJ, 386 MJ, 274 MJ, 154 MJ, 276 MJ, and 511 MJ per kg of active ingredient (a.i.) for fungicides, herbicides, insecticide, molluscicide, growth regulator, and seed treatment production, respectively, with an average of 370 MJ. To convert energy (MJ) to $CO_{2\text{-eq}}$ per kg of a.i., a factor of 0.069 (kg $CO_{2\text{-eq}}$ per MJ of pesticide energy) was used [32].

The total emissions from tractors, implements, sugarcane, and coffee harvesters were calculated using the quantity of machinery used per hectare times the respective ratio weight (kg)–life cycle (year) and the EFs for machinery, sugarcane, or coffee harvesters. The estimated EF for machinery (including sugarcane and coffee harvesters) was obtained from Mantoam et al. (2020) [34]; the amounts of $CO_{2\text{-eq}}$ emitted during the assembly phase and repairs (kg $CO_{2\text{-eq}}$) were divided by the corresponding mass, in kilograms. Similarly, emissions for machinery diesel combustion were determined using the quantity of machinery used per hectare times the potency in kW, a factor of 0.163, and the EF for diesel.

Other factors and emissions EF used during calculation were: (i) 0.115 kg of $CO_{2\text{-eq}}$ for kg of seed potato [35]; (ii) 0.0426 kg of $CO_{2\text{-eq}}$ for kg of cassava for planting [36] and 630 kg m^3 for cassava density [37]; (iii) 0.87 kg of $CO_{2\text{-eq}}$ for kg of seeds [38–41] and 1.74 kg of $CO_{2\text{-eq}}$ for each seedling; (iv) 1.64 kg of $CO_{2\text{-eq}}$ for kg of firewood [42]; (v) 0.41 kg of $CO_{2\text{-eq}}$ per working hour [43] and 2.2 MJ per hour for human labor [44]; and (vi) 0.052 kg of $CO_{2\text{-eq}}$ per MJ for electricity [33].

Factors of emissions above described are summarized in Table 3.

Table 3. Factors of emissions to direct and indirect inputs.

Input	Unit	Production [3]	Direct [4]	Indirect [5]	Total
		----------------------------kg $CO_{2\text{-eq}}$ [1]----------------------------			
Nitrogen	kg	3.53	1.35	0.54	5.42
P_2O_5	kg	0.54	-	-	0.54
K_2O	kg	0.61	-	-	0.61
Lime	kg	0.07	0.46	-	0.53
Poultry manure	kg		0.12	0.02	0.14
Fungicide	kg a.i. [2]	29.10	-	-	29.10
Herbicide	kg a.i.	26.60	-	-	26.60
Insecticide	kg a.i.	18.90	-	-	18.90
Other chemicals	kg a.i.	25.50	-	-	25.50
Seeds	kg	0.87			
Seedlings	kg				
Machinery	kg	3.90	-	-	3.90
Sugarcane harvester	kg	9.53	-	-	9.53
Coffee harvester	kg	4.89	-	-	4.89

[1] The 100-years global warming potentials (GWPs) for methane (CH_4) and nitrous oxide (N_2O) are 25 and 298, respectively [36]. [2] a.i corresponds to active ingredient. [3] Fertilizers' production emission factors were obtained in [19]. Pesticides' production emission factors were obtained from [24]. Seeds' and seedlings' emission factors were obtained in [38–41]. Machinery, sugarcane, and coffee harvester emission factors (assembly and maintenance and repair) were obtained in [26]. [4] Direct emissions from managed soil were calculated using [20,21,27]. [5] Indirect emission factors (N volatilized and deposition and N leaching) were calculated using [21].

3. Results

As agriculture has a fundamental contribution to GHG emissions currently counting up to 21% of $CO_{2\text{-eq}}$ emissions and with 14% of CO_2 only emissions worldwide including agriculture, livestock, forestry, and other land use changes [9], the results of this assessment attempt to detail the main sources of direct and indirect emissions through the analyses of various crops described in the methodology section.

Direct and Indirect Emissions

On average, indirect emissions are responsible for 36% of the emissions, meanwhile direct emissions area are responsible for 64%. Most of the direct emissions are due to the consumption of fertilizers and pesticides by the crops assessed.

Proportionally, Castor Bean System 1 has the highest indirect emissions with this category accounting for 62% of the emissions mainly from labor, while coffee has the highest direct emissions contributing 83% of the emissions mainly from fertilizers.

This result shows that crops with high mechanization but lower input needs such as fertilizers or pesticides have lower $CO_{2\text{-}eq}$ emission rates.

The main results are shown in Figures 2 and 3.

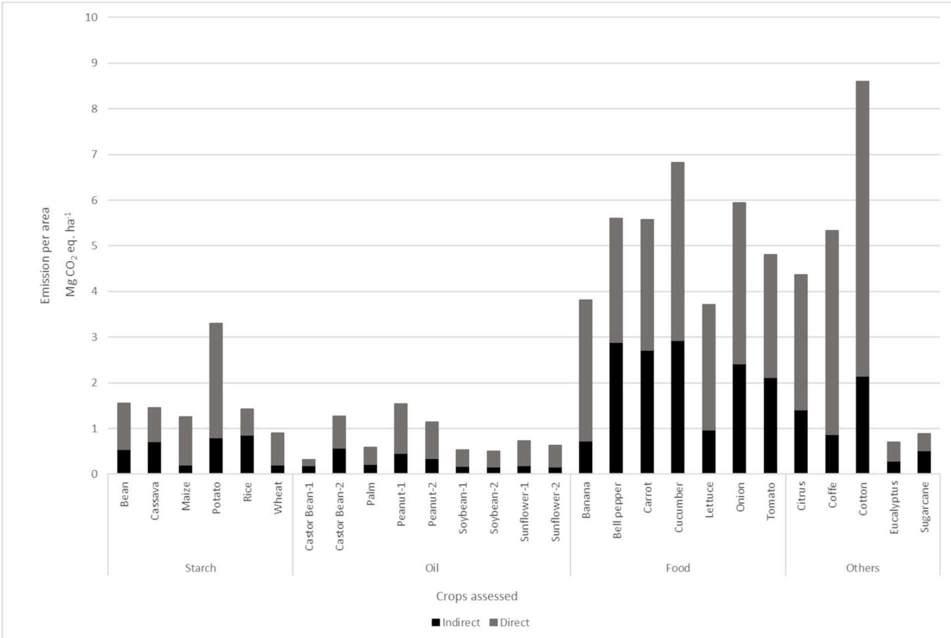

Figure 2. Direct and indirect emissions per area.

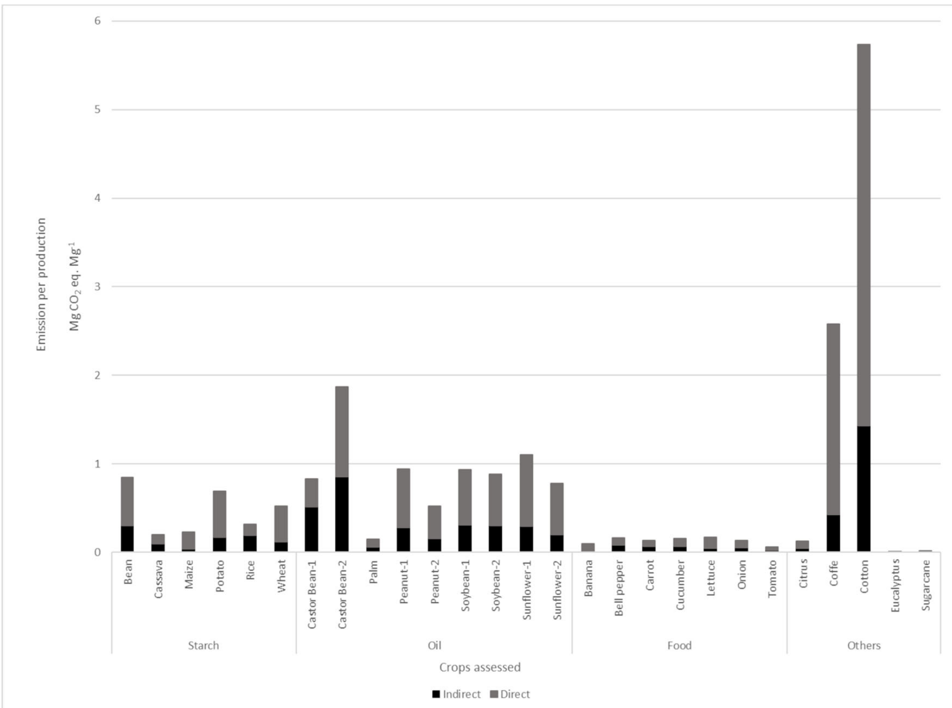

Figure 3. Direct and indirect emissions per production.

4. Discussion

4.1. Assessment by Area

The average emission of the considered crops, per area, is 2728.78 kg $CO_{2\text{-eq}}$ ha^{-1}. Cotton is the crop with the highest emissions per area with 8602.00 $CO_{2\text{-eq}}$ ha^{-1}, mainly by direct inputs with fertilizers and chemicals that together represent 75% of all emissions. On the other hand, Castor Bean System 1 has the lowest emissions with 315.071 $CO_{2\text{-eq}}$ ha^{-1}, with most of them coming from direct inputs, mainly from labor with 39% of the emissions. The main fact that contributes to these crops is the level of technification adopted on average for each crop, while in Castor Beans System 1, there are a lower technical adoption rate and low direct inputs; crops with a high necessity for pesticides like cotton will have increased emissions per area.

Overall, oil crops have the lowest average emissions; meanwhile, food crops have the highest values. This result is due to the higher direct inputs for food crops, while some oil crops like soybeans have a smaller fertilizer input due to them having no need of nitrogen fertilizer.

A resume of the emissions among crops classification is demonstrated in Figure 4.

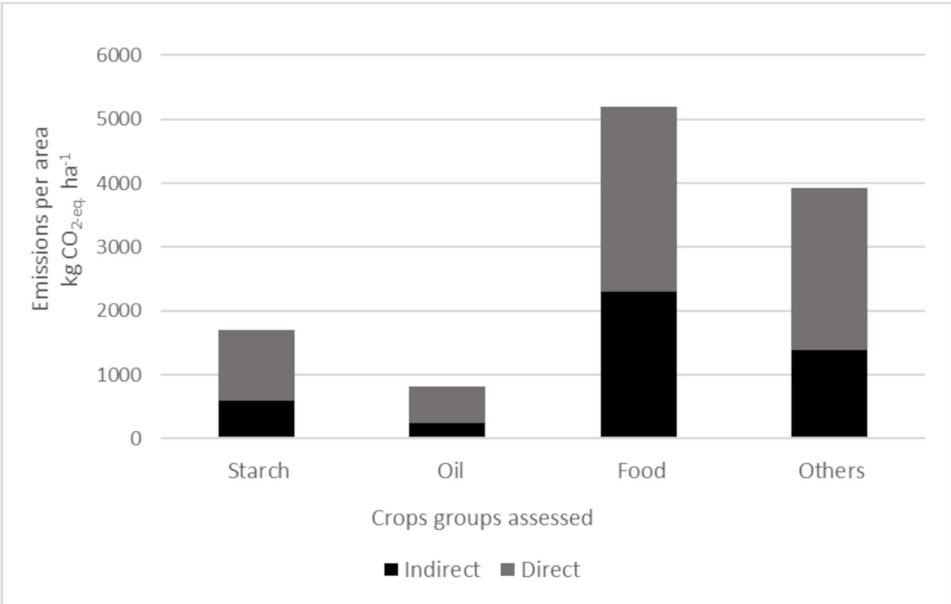

Figure 4. Average emissions per area per group of crops.

Oilseed crops generally have lower emissions due to lower amounts of fertilizer use, either because they are more rustic crops or more rudimentary production systems, as in the case of castor beans, while soybeans have low emissions due to nitrogen fixation by the plant, which makes nitrogen fertilization unnecessary.

Food crops have the highest emissions per area of which direct input with fertilizers accounts for 58%, in average, of total emissions.

4.2. Assessment by Production

The average emission of the considered crops, per product, is 749.53 kg $CO_{2\text{-eq}}$ Mg^{-1} with cotton showing the highest emissions per product with 5734.67 kg $CO_{2\text{-eq}}$ Mg^{-1}, while eucalyptus shows the lowest emissions per product with 2.42 kg $CO_{2\text{-eq}}$ m^{-3}, which has a different functional unit (FU), but in mass it is equivalent to around 720 kg, and even if converted into Mg, it would have the lowest emission value.

Assessing the crops by their production, food crops have the lowest emissions, while the group of others crops has higher emissions, mainly because of the contribution of cotton and coffee that have high inputs and lower productions, as can be seen in Figure 5.

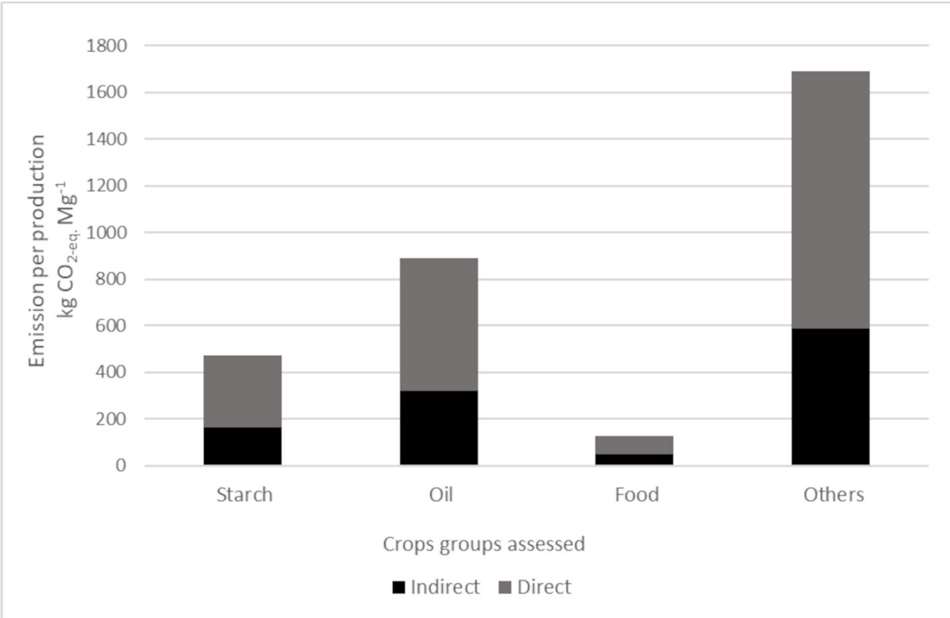

Figure 5. Average emissions per production per group of crops.

4.3. Assessment by Crop Groups

As both food and other crops have their own final FU, they will not be assessed by their groups.

In starch crops, wheat has the lowest emissions per area, mainly because of they have the lowest input in indirect emissions, while potato has the biggest emissions, mostly because of direct emissions with chemicals accounting for 48% of $CO_{2\text{-eq}}$ emissions.

Considering the FU, cassava has the lowest emissions, which shows the potential of the development of this crop to produce starch in a more environmentally friendly way. Maize and rice are also crops with lower emissions.

Despite beans having large emissions per FU, starch is not only the main benefit of this crop that has, as well, a high content of protein, which is not counted in this work but mut be take into account for nutrition purposes.

As for oil crops, there were different systems analyzed; there are some crops that have a high emission value in one system and a very low value in another system, like peanut in system 1 which has the third highest emission of $CO_{2\text{-eq}}$ Mg^{-1}; meanwhile, system 2 has the second lowest emissions per production.

Overall, Castor Beans System 2 has the highest emissions per Mg of oil produced mainly because the increase in machinery, diesel, and fertilizers used results in about three times more $CO_{2\text{-eq}}$ emission ha^{-1} with no such increment in the crop and oil yield that was 76% higher.

Palm oil showed the lowest emissions per production, mainly due to its low emissions per area and higher yield of production, characteristic of this crop.

4.4. Comparison between Crops with Different Systems of Production

Considering crops that have two systems of production like castor bean, peanut, sunflower, and soybean, it is possible to compare their emissions demonstrating better practices for each crop between the scenarios evaluated.

For all four crops with two systems, there is an increase of kg $CO_{2\text{-eq}}$ Mg^{-1} in systems with a higher input of fertilizers or chemicals, demonstrating that the increase in yield did not compensate the increase in the inputs. Of course, this does not consider that lower yields will need more area or deforestation producing LUC emissions.

4.5. Comparative Evaluation

To assess the results of this study, a comparison with previous studies was made to check if the emissions calculated are in line with other methodologies adopted.

The data from the other studies were selected to comprise the same boundaries used in this study; that would be, if the study assesses emissions from LUC or processing to final products, like soybean oil or starch from cassava, it was considered to be only the farm portion of the emissions. Moreover, the unit was adjusted to the same ones used in this study, kg of $CO_{2\text{-eq}}$ Mg^{-1}. The results of the comparison are shown in Table 4.

Table 4. Comparison of results between this study and the literature consulted.

Group	Crop	Emissions (kg $CO_{2\text{-eq}}$ Mg^{-1})		Observation
		Present Study	**Literature**	
Food	Banana	95.23	266.00 [1]	Yield considered is almost half of the average Brazilian yield
Food	Bell pepper	160.04	NF	
Food	Carrot	132.52	154.00 [1]	
Food	Cucumber	155.14	NF	
Food	Lettuce	165.85	NF	
Food	Onion	136.09	211.00 [1]	
Food	Tomato	56.52	704.00 [1]	Literature consulted considered tomatoes produced in greenhouses with temperature control
Oil	Castor Bean-1	823.72	815.00 [2]	
Oil	Castor Bean-2	1873.11	1667.50	
Oil	Palm	148.59	2172.16 [1]	This study considered a very low mechanized system comparing with other production systems
Oil	Peanut-1	945.38	548.08 [1]	
Oil	Peanut-2	516.65	548.08 [1]	
Oil	Soybean-1	938.22	1633.33 [1]	
Oil	Soybean-2	888.30	1633.33 [1]	
Oil	Sunflower-1	1105.29	558.48 [1]	
Oil	Sunflower-2	775.69	558.48 [1]	
Others	Citrus	128.38	307.00 [1]	
Others	Coffee	2583.02	10,386.00 [1]	Literature considered as a farm process depulping and roasting, not considered in this study
Others	Cotton	5734.67	3270.00 [3]	
Others	Eucalyptus	2.42	2.07 [4]	Average on literature results
Others	Sugarcane	11.46	72.75 [1]	Literature considered the burning of residues
Starch	Bean	849.35	811.48 [1]	Average pulses considered by literature and not only *Phaseolus vulgaris* like this work
Starch	Cassava	195.51	663.65 [1]	Literature considered cassava yield half of what was considered at this study
Starch	Maize	230.42	183.94 [1]	
Starch	Potato	746.45	1652.40 [1]	
Starch	Rice	318.55	964.18 [1]	Literature counting methane emissions from flooding system
Starch	Wheat	520.69	491.07 [1]	

[1] [45]; [2] [46]; [3] [47]; [4] [48]; NF—Not found.

Among the differences identified between this study and others compared, there are notable points regarding agricultural practices or productivity that vary significantly from the parameters of the proposed methodology, which are described in the table observations when identified. However, there is a tendency indicating that the methodology presented here remains consistent across different crops and serves as an effective means of comparing diverse crops with varying practices. Results show high differences in are due to the different boundaries or functional units adopted, yet they still show crops with higher $CO_{2\text{-eq}}$ emissions like coffee which is found to have the greatest difference, mainly because of the processes of depulping and roasting with high emissions, but still showing this crop as one with high emissions in comparison with other crops in general.

The study showed this methodology has a good strength to estimate $CO_{2\text{-eq}}$ emissions and can be used as an approach to compare different systems of production or different sources of the same product such as starch, oil, or sugar ensuring that they are all at the same basis of comparison.

Furthermore, in terms of using reports of costs, reports produced by machinery used in agricultural crops can be used, increasing the precision of the results to each operation itself, even more so with the increasing adoption of agricultural machines with increasingly embedded sensor technology and on-board computers. For this aspect, since the end of the last century, there has been a large increase in the use of computers, the global positioning system, and a huge variety of sensors used to oversee the various operations carried out in agriculture [49,50].

This assessment, improved with detailed data from digital agriculture, can clearly show that some practices such as crop rotation, agroforestry, precision agriculture, genetically modified crops among other agricultural practices are better at estimating which ones are more environmentally suitable under the same basis of comparison, even though digital agriculture faces great barriers, in Brazil, such as the lack of connectivity in rural areas, high implementation and maintenance costs, and the need for technical training. Public incentives, investment in infrastructure, and training programs are essential to overcome these challenges and promote agricultural modernization and should happens gradually in the agricultural sector.

This study can be used as a source of comparison for policy recommendations to be adopted in different regions aiming to reduce GHG emissions in a broad conservation program like the Adaptation and Low Carbon Emissions Plan in Agriculture known as the ABC+ Program adopted in Brazil [51].

From the economic perspective, there is the possibility of an increase in added value to products that are proven to be more environmentally friendly in comparison with distinct production systems that have higher GHG emissions.

Despite the benefits, it may be difficult to obtain more detailed data on several rustic crops or from farmers that refuse to share or make public their data [52], which is why collaborative approaches among the different players like the government, farmers, industries, and research institutions are essential to encourage the adoption of such an evaluation.

5. Conclusions

This study evaluated the direct and indirect greenhouse gas (GHG) emissions of various crops, including castor bean, coffee, cotton, eucalyptus, soybean, potato, wheat, corn, rice, peanuts, sunflower, and palm. The results showed that indirect emissions account for 36% of the total, while direct emissions account for 64%. These results highlight the importance of considering both direct and indirect emissions when assessing the environmental impact of crops. They also provide insights into production practices that contribute to higher emissions, such as the intensive use of fertilizers and pesticides. Nevertheless, more detailed data on traditional crops and specific production systems would improve the accuracy of the results.

In the broader context of sustainable agriculture, this assessment contributes to a deeper understanding of crop GHG emissions and informs policies and practices that can mitigate climate change. We believe that our results will be valuable to researchers, policymakers, and farmers seeking to reduce the environmental impact of agricultural production. Moreover, they will encourage collaboration among governments, farmers, industries, and research institutions to promote the adoption of more sustainable agricultural practices. By sharing data and adopting digital technologies, we can improve the accuracy of GHG emission assessments and identify effective strategies for reducing emissions and mitigating climate change.

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