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Life Cycle Greenhouse Gas Emissions in Maize No-Till Agroecosystems in Southern Brazil Based on a Long-Term Experiment

Guilherme Rosa da Silva [1], Adam J. Liska [2,*] and Cimelio Bayer [1]

[1] Department of Soil Science, Federal University of Rio Grande do Sul, 7712 Bento Gonçalves Ave., Porto Alegre 91540-000, RS, Brazil; mutadagui@gmail.com (G.R.d.S.); cimelio.bayer@ufrgs.br (C.B.)
[2] Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
* Correspondence: aliska2@unl.edu

Abstract: Brazilian agriculture is constantly questioned concerning its environmental impacts, particularly greenhouse gas (GHG) emissions. This research study used data from a 34-year field experiment to estimate the life cycle GHG emissions intensity of maize production for grain in farming systems under no-tillage (NT) and conventional tillage (CT) combined with Gramineae (oat) and legume (vetch) cover crops in southern Brazil. We applied the Feedstock Carbon Intensity Calculator for modeling the "field-to-farm gate" emissions with measured annual soil N_2O and CH_4 emissions data. For net CO_2 emissions, increases in soil organic C (SOC) were applied as a proxy, where the CT combined with oat was a reference. The life cycle GHG emissions intensity for maize was negative under NT farming systems with Gramineae and legume cover crops, −0.7 and −0.1 kg CO_2e kg^{-1} of maize, respectively. CT with oats as a cover crop had a GHG intensity of 1.0 kg CO_2e kg^{-1} of maize and 2.2 Mg CO_2e ha^{-1}. NT with cover crops increased SOC (0.7 C Mg ha^{-1} yr^{-1}, 0–100 cm) and contributed to the mitigation of life cycle GHG emissions of maize production. This research shows that NT with cover crops is a sustainable solution for farming in southern Brazil.

Keywords: cover crops; greenhouse gas emissions; maize; no-till; soil organic carbon; sub-tropical Brazil

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1. Introduction

A quarter of global greenhouse gas (GHG) emissions are from agriculture, forestry, and other land use (AFOLU) sectors, mainly as nitrous oxide (N_2O) and methane (CH_4) emissions [1–3]. Brazil is the seventh largest emitter of GHGs in the world, being responsible for ~3% of global emissions [4]. Brazil's agricultural sector accounts for 25% of national GHG emissions [4], being responsible for 87% of N_2O and 76% of CH_4 emitted nationally [5]. Fertilizer and manure management is responsible for 28% of agricultural GHG emissions [4], and is the main source of N_2O emissions. The management of soil is responsible for 30% of GHG emissions from the agriculture sector. Around 50% (~33 million hectares) of the area cultivated with grains in Brazil is under NT, and just over 20 million hectares is under maize [6,7]. Maize is a major crop in the global food system, serving as food for both humans and livestock, and is the second most produced food commodity in the world. After the USA and China, Brazil is the third largest global producer, with 132 million tons of maize in 2022/2023 [8].

Soil tillage operations determine different ranges of fuel consumption and have different environmental impacts [9]. Sørensen et al. [10] found the NT systems reduced total energy input by 41% compared to CT on average. Environmental impacts from tillage can also influence crop growth, as well as soil properties that can increase or decrease GHG emissions and soil C sequestration [11–13]. The effect of tillage systems on soil emissions is possibly related to alterations in soils' physical, chemical, and biological characteristics [14–17]. Bayer et al. [14] found higher N_2O emissions for CT than NT, both with oat and maize in rotation, in a long-term experiment in southern Brazil. CT systems create an unfavorable environment for methanotrophic organisms because of soil disturbance [18–21]. Bayer et al. [22] found that under an NT system, CH_4 consumption (oxidation) increased a little due to the positive effects on biological, chemical, and physical soil quality indicators. According to Bayer et al. [22], recovery of soil CH_4 oxidation capacity requires several decades to significantly affect conservation management systems to mitigate CH_4 emissions from soil. Many regional studies in southern Brazil have found that the use of NT systems provides increased C sequestration, ranging from 0.19 to 1.15 C Mg ha^{-1} yr^{-1} compared to CT [23,24]. Lehman and Osborne [25] found that the GHG emissions (N_2O, CH_4, and CO_2) were roughly half of soil organic carbon (SOC) (0–30 cm) gains with maize residue removal under NT practices that improved the viability of biennial maize residue harvest. Previous research has found that NT systems provide a lower GHG emissions intensity than CT [17,23,26–31], illustrating the potential of conservation agriculture to mitigate GHG emissions. Bayer et al. [26] found that conservation management systems can have negative emission values ranging from −196 to −614 kg CO_2e Mg^{-1} of maize yield, due primarily to SOC sequestration. Holka and Bieńkowski [32] found GHG emissions from maize grain cultivated in Poland under NT was 480 kg CO_2e ha^{-1} less than CT. Li et al. [33] found that NT reduced GHG emissions intensity by 14.4% compared to CT, but did not change crop yields. The potential to mitigate GHG emissions in farm systems appears to be dependent not only on NT but also on what and how many crops are present in the cropping systems.

Cropping systems can increase soil nutrients, mainly from N fertilization or from the use of legume cover crops, but both consequently increase soil N_2O emissions [26,34–39]. The effect of higher N availability can increase soil N_2O emissions in the cropping system with legume compared to Gramineae, regardless of the soil tillage system [14,34,37,39,40]. However, Bayer et al. [26] found that NT soil under a legume crop has six times greater CO_2 retention rates than annual soil N_2O emissions (in CO_2e). Long-term cropping systems also influence the CH_4 oxidation capacity of soils, mainly with cropping systems that have a high C input which can improve the quality of soil [22]. Cropping systems can also improve the C sequestration of soil by the amount and quality of C input into the soil under NT systems [41,42]. Studies have shown that cropping systems with high C input and NT systems under conservation agriculture principles can have C sequestration rates from 0.19 to 0.51 C Mg ha^{-1} yr^{-1} in tropical and subtropical soil in Brazil to a soil depth of 0 to 30 cm [23,24]. When Veloso et al. [24] evaluated C sequestration for a soil depth of 0 to 100 cm, C sequestration varied from 0.38 to 1.15 C Mg ha^{-1} yr^{-1}. Approximately half of C sequestration occurred in the layer from 0 to 30 cm, and another ~50% in the layer from 30 to 100 cm [24]. According to Bayer et al. [26], soil under NT with legume cover crops acts as a net sink of GHG in the long term in southern Brazil.

Faced with environmental pressures from agriculture, researchers have analyzed the environmental impacts of agroecosystems using Life Cycle Assessment (LCA), which is considered a reference methodology for the assessment of the environmental impacts of product systems [43]. We hypothesized that the impact of soil management practices on soil GHG emissions might be lower under NT compared to CT, and life cycle GHG emissions will be decreased under NT. The objective of this research is to analyze the LCA of maize in a long-term experiment and the effects of tillage and cropping systems on GHG emissions from a subtropical Acrisol in southern Brazil. LCA has the advantage of flexible system boundaries and metrics for the evaluation of the environmental impacts of a product, but the flexibility of the method can lead to variable system boundaries and conflicting results using similar types of data [44]. Yet, in this study of the maize life cycle, the system has a fixed system boundary based on the model we applied, which overcomes the difficulty of unnecessary variability in results.

2. Materials and Methods

2.1. Site Description and Field Experimental Design

This LCA study used field data from a long-term field experiment initiated in 1985. The site of the experiment is at the Farm Experimental of the Federal University of Rio Grande do Sul (EEA/UFRGS) and is located at geographic coordinates 30°50′52″ S and 51°38′08″ W, in Eldorado do Sul, Rio Grande do Sul, Brazil. The area was under native grassland (i.e., *Paspalum* spp. and *Andropogon* spp.) that is typical of native vegetation of the southern region of Brazil. In 1969, the area was converted to cropland under conventional tillage, with plowing and disking that promoted soil degradation, and was cultivated with small-grain crops from 1969 to 1984 [24]. The soil is classified as a sandy clay loam Acrisol [45] or Typic Paleudult according to Soil Taxonomy [46].

The long-term experiment consists of the combination of two tillage systems, CT and NT systems, with two cropping systems: (i) oat (*Avena strigosa Schreb*) in the winter season and maize (*Zea mays* L.) in the summer season (oat/maize designated here as O/M); and (ii) vetch (*Vicia sativa* L.) in the winter season and maize in the summer season (vetch/maize designated here as V/M). The experiment is in a randomized block experimental design with split plots and three replicates in all treatments where tillage systems are assigned to the main plots (15 × 20 m) and cropping systems to the subplots (5 × 20 m) [24].

Winter crops were managed as cover crops, established from April to May each year, using direct drilling in CT and NT farming systems. Oat was seeded at a rate of 80 kg ha^{-1}, and vetch was seeded at 50 kg ha^{-1} [24].

The agricultural activities made in CT were plowed once a year in spring before maize planting and harrowed twice for mixing crop residues into the soil. Glyphosate-based herbicide (Roundup®; Bayer, Leverkusen, Germany) was applied in the NT systems at 1.4 kg ha^{-1} concerning final glyphosate concentration, and the winter cover crops were managed with a crimper roller, with the aboveground residues left on the soil surface [24]. In NT, soil disturbance occurred only in the sowing line [24]. Maize was planted with an NT planter in both tillage treatments in September–October to obtain ~50–70 thousand plants per hectare [24].

2.2. Goal and Scope of the LCA

The goal of this study is to provide a GHG emissions assessment of maize production in southern Brazil, comparing the use of different combinations of two tillage systems (CT and NT), and two cover crops (Gramineae and legume): CT O/M, CT V/M, NT O/M, and NT V/M. The study was based on the LCA methodology using the Feedstock Carbon Intensity Calculator (FD-CIC), a field-to-farm gate model derived from the GREET model (https://greet.anl.gov/tool_fd_cic; accessed on 1 December 2023) [47]. The system boundary of our analysis is limited to field-to-farm gate activities since we aim to quantify the GHG emissions intensity of the crops at the feedstock level (Figure 1). Three GHG emissions (CO_2, CH_4, and N_2O) were quantified. The energy and material flows from upstream chemical manufacturing and feedstock production stages were quantified. In this study, we used two functional units to describe GHG emissions from our agroecosystem: (i) metric tons per hectare per year, and (ii) emissions per kg of maize per year.

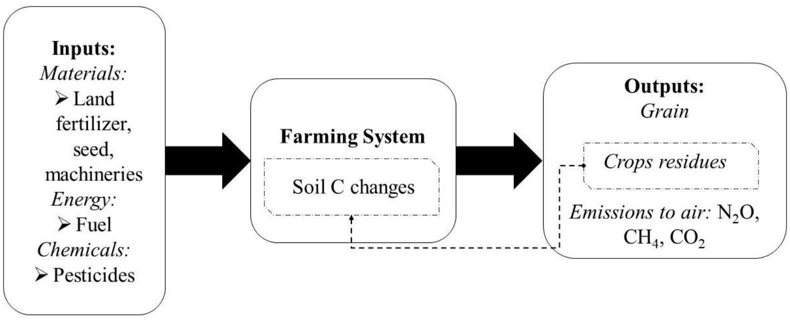

Figure 1. System boundaries of the life cycle of grain maize production from "field-to-farm gate".

2.3. Data Collection and Inventory Data

GHG emission data were measured in the long-term experiment for the main GHGs, N_2O and CH_4, in the 2003/2004, 2009/2010, 2010/2011, and 2011/2012 seasons.

In 2003/2004, collections were weekly for 45 days after soil tillage, continuing after that with approximately monthly collections for up to 12 months. In the 2009/2010 season, collections were carried out from October 2009 to October 2010, starting 14 days after the management of cover crops, with 27 assessments carried out at 14, 18, 21, 24, 28, 31, 34, 42, 52, 59, 73, 80, 87, 117, 131, 145, 159, 178, 199, 255, 262, 283, 304, 318, 340, 358, and 381 days after cover crop management. In the 2010/2011 and 2011/2012 seasons, collections began on the first and third days after the soil tillage and management of cover crops; collections were more frequent up to 60 days after management and subsequently carried out at intervals of approximately 15 days. In the 2010/11 season, 25 collections were carried out at 1, 9, 13, 16, 21, 30, 37, 51, 65, 84, 97, 119, 135, 153, 168, 189, 201, 215, 229, 243, 257, 271, 285, 313, and 324 days after soil tillage. In the 2011/12 season, 33 collections were carried out after soil tillage at 3, 5, 7, 9, 13, 16, 20, 22, 27, 29, 35, 40, 48, 55, 64, 71, 90, 114, 125, 140, 156, 176, 187, 202, 215, 230, 250, 264, 278, 292, 307, 323, and 341 days.

To measure gas emissions, the chamber method was used, which was composed of two modules: (i) an aluminum base (40 × 80 cm) inserted into the ground at a depth of 5 cm, and (ii) an aluminum top with the same dimensions, which was fitted onto the aluminum base during collection, constituting the sampling chamber. The top has a carrying handle and holes to which the digital thermometer, the air collection extender, and the wiring for connecting the battery are connected. Internally, the chamber features two cooler-type fans for homogenizing the chamber atmosphere before sampling.

Air collections were conducted between 9:00 and 11:00 am, and emissions were considered equivalent to average daily emissions. Collections were carried out using BD® polypropylene syringes with a volume of 20 mL, which were stored in a Styrofoam box at a low temperature.

Gas chromatography was used at the Environmental Biogeochemistry Laboratory of the Federal University of Rio Grande do Sul for analysis of the samples. Quantification was carried out using GC Shimadzu 2014 equipment, model "Greenhouse" with the following chromatographic conditions: Porapak-Q column with the temperature at 70 °C, N_2 carrier gas at 30 mL min^{-1}, methanator at 380 °C, FID detector at 250 °C, and ECD at 325 °C.

We used the annual average of N_2O and CH_4 emissions to calculate our field study's GHG emissions intensity (Table 1).

Table 1. N_2O and CH_4 emissions from farming systems and research thesis sources.

Thesis	Year	Units	Farming Systems							
			CT O/M		CT V/M		NT O/M		NT V/M	
			N_2O	CH_4	N_2O	CH_4	N_2O	CH_4	N_2O	CH_4
Gomes [48]	2003/2004	kg ha^{-1} yr^{-1}	1.3	0.8	0.5	−2.2	−0.4	0.5	1.4	0.7
Alcalde [49]	2009/2010	kg ha^{-1} yr^{-1}	24.0	−3.8	41.3	−7.4	8.0	−9.0	21.2	−10.1
Denega [50]	2010/2011	kg ha^{-1} yr^{-1}	1.2	−0.3	1.5	−0.2	0.6	−0.4	1.2	−0.7
	2011/2012	kg ha^{-1} yr^{-1}	0.6	−1.0	1.6	−0.5	0.3	−1.4	0.7	−0.5
Average		kg ha^{-1} yr^{-1}	6.7	−1.1	11.2	−2.6	2.1	−2.6	6.1	−2.7

We used the C sequestration rate as the proxy of net CO_2 fluxes in soil management treatments taking the CT O/M as the reference control. The soil C data were available in Veloso et al. [24] and the annual C storage rates were calculated for 0 to 30 cm and 0 to 100 cm soil depths (Table 2).

Table 2. Soil organic C (SOC) stocks and SOC storage rates. Reprinted with permission from reference [24]. Copyright 2018 Elsevier.

Farming Systems		SOC Stocks			SOC Storage Rates		
		0–30 cm	30–100 cm	0–100 cm	0–30 cm	30–100 cm	0–100 cm
Tillage	Crops	C Mg ha^{-1}			C Mg ha^{-1} yr^{-1}		
CT	O/M	47.9	71.7	119.6	0 *	0 *	0 *
CT	V/M	53.8	79.4	133.2	0.15	0.27	0.42
NT	O/M	51.7	87.8	139.5	0.13	0.53	0.66
NT	V/M	54.6	85.9	140.5	0.22	0.48	0.7

* This treatment does not have SOC storage rates because it was the reference to calculate SOC rates in the other treatments.

We calculated the average maize crop yield of the farming systems in the experiment from the 1985/86 season to 2021/22, except for the results of the 2019/20 season where the samples were not taken because of the COVID-19 pandemic.

The LCA inventory data for net relative soil GHG emissions were estimated.

2.4. Life Cycle Impact Assessment Modeling

Data from the long-term experiment were incorporated into the FD-CIC dynamic version 2022. This version allows the users to change the FD-CIC default settings that affect the GHG emission intensities of the farming inputs. To run the model, the initial step involved inputting production information for maize production for one season into the "Maize Inputs" sheet. All the relevant values were recorded in the "User Specific Value (NT)" or "Default GREET(CT)" columns.

Several modifications were made to the "Maize Results" sheet to incorporate measurements from the long-term experiment. Specifically, the values for "N_2O emission due to nitrogen fertilizer and biomass residue" in row 18 were set to zero. Instead of relying on model calculations for this variable, the actual measured C sequestration data, methane emissions data, and N_2O emissions data were included in rows 37, 38, and 39, respectively, following the necessary unit conversions.

3. Results

3.1. Life Cycle Inventory Analysis

The study collected the LCI data from the FD-CIC model, focusing on the inventory related to impact assessment on climate change, such as CO_2, NO_2, CH_4, and SOC. The life cycle inventory databases were created for maize production for grain for each of the studied tillage systems (Tables 3 and 4).

Table 3. LCI annual data input of farming systems.

Annualized Farming Input Parameters	CT O/M	CT V/M	NT O/M	NT V/M	Unit
Farm size	1	1	1	1	hectare
Maize yield	2318	4401	2342	4797	kg ha^{-1}
Diesel	28.1	28.1	3.8	3.8	L ha^{-1}
Triple Superphosphate	50	50	50	50	kg ha^{-1}
K_2O	50	50	50	50	kg ha^{-1}
$CaCO_3$	167	167	167	167	kg ha^{-1}
Herbicide	6.3	6.3	6.3	6.3	kg ha^{-1}

Table 4. Annual GHG emissions from the farming systems by kg and per hectare.

Annualized Farming Output	CT O/M	CT V/M	NT O/M	NT V/M	Unit
Diesel	39.0	20.5	5.2	2.5	g CO_2e kg^{-1}
Phosphorus Fertilizer P_2O_5	10.1	5.3	10.0	4.9	g CO_2e kg^{-1}
Potash Fertilizer K_2O	2.5	1.3	2.4	1.2	g CO_2e kg^{-1}
Lime $CaCO_3$	0.1	0.1	0.1	0.1	g CO_2e kg^{-1}
CO_2 emission due to $CaCO_3$ use	3.2	1.7	3.2	1.6	g CO_2e kg^{-1}
Herbicide	51.3	27.0	50.8	24.8	g CO_2e kg^{-1}
SOC 0–30 cm	0	−125.1	−203.7	−168.3	g CO_2e kg^{-1}
SOC 30–100 cm	0	−225.2	−830.6	−367.2	g CO_2e kg^{-1}
CH_4 Chamber	−11.6	−14.8	−27.9	−13.8	g CO_2e kg^{-1}
N_2O Chamber	867.6	759.4	269.2	381.1	g CO_2e kg^{-1}
Total GHG emissions	962.3	450.6	−720.3	−132.8	g CO_2e kg^{-1}
Emissions per hectare					
Diesel	90.4	90.4	12.2	12.2	kg CO_2e ha^{-1}
Phosphorus Fertilizer P_2O_5	23.5	23.5	23.5	23.5	kg CO_2e ha^{-1}
Potash Fertilizer K_2O	5.7	5.7	5.7	5.7	kg CO_2e ha^{-1}
Lime $CaCO_3$	0.3	0.3	0.3	0.3	kg CO_2e ha^{-1}
CO_2 emission due to $CaCO_3$ use	7.4	7.4	7.4	7.4	kg CO_2e ha^{-1}
Herbicide	119.0	118.9	118.9	118.9	kg CO_2e ha^{-1}
SOC 0–30 cm	0	−550.5	−477.1	−807.4	kg CO_2e ha^{-1}
SOC 30–100 cm	0	−990.9	−1945.1	−1761.6	kg CO_2e ha^{-1}
CH_4 Chamber	−26.9	−65.0	−65.3	−66.3	kg CO_2e ha^{-1}
N_2O Chamber	2011.1	3341.9	630.4	1828.0	kg CO_2e ha^{-1}
Total GHG emissions	2230.6	1983.1	−1687.0	−637.1	kg CO_2e ha^{-1}

3.2. Sources of GHG Emissions

The results of the FD-CIC model for GHG emissions show that the most important source of GHGs into the atmosphere was N_2O, although no N fertilization was performed (Figures 2 and 3). The soil N_2O emissions varied from 269.2 to 867.6 g CO_2e kg^{-1} of maize, where farming systems using NT had lower emissions than the farming system with CT system. When observed on a hectare basis, higher emissions occurred in the CT systems, with the highest N_2O emission in CT V/M (Figure 3). The V/M cropping systems with N_2 fixing legume cover crop (vetch) had higher N_2O emissions than O/M in both tillage systems on a hectare basis (Figure 3). The NT O/M had the lowest N_2O emissions per hectare, 630.4 kg CO_2e ha^{-1}. In general, the soil was a sink of CH_4 in the farming systems (due to oxidation of CH_4 to CO_2); the CH_4 influx was from −26.9 to −66.3 kg CO_2e ha^{-1}. The V/M cropping systems had a lower influx than O/M, with the highest influx in the NT O/M farming system. The C sequestration for different (CT V/M, NT O/M, and NT V/M) farming systems in the soil layer 0–30 cm depth was from 125.1 to 203.7 g CO_2 kg^{-1} of maize and from 477.1 to 807.4 kg CO_2 ha^{-1} (Table 4). In the deep soil layer 30–100 cm, C sequestration was from 225.2 to 830.6 g CO_2 kg^{-1} of maize and from 990.9 to 1945.1 kg CO_2 ha^{-1} (Table 4). For the total soil layer 0–100 cm, C sequestration was from 350.2 to 1034.3 g CO_2 kg^{-1} of maize and from 1541.4 to 2569.0 kg CO_2 ha^{-1}. Taking the annual rates of soil C variation in comparison to a CT O/M reference as a proxy, the CO_2 emissions from soil were estimated to be from −1033 to 3 g CO_2e kg of $maize^{-1}$, and from −2566.9 to 7.8 kg CO_2e ha^{-1}. The NT O/M farming system had the lowest CO_2 emissions per kg of maize, while NT V/M had the lowest CO_2 emissions per hectare.

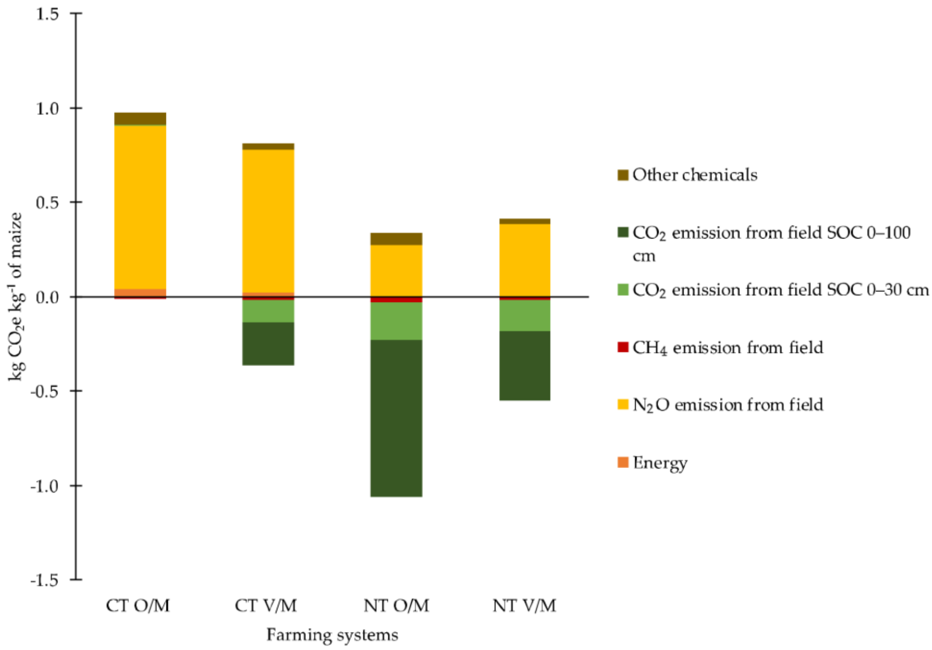

Figure 2. Life cycle GHG emissions per kg of maize from farming systems for each source. Net annual soil CO_2 emissions were calculated by taking annual soil C storage rates in farming systems in relation to CT O/M system (control).

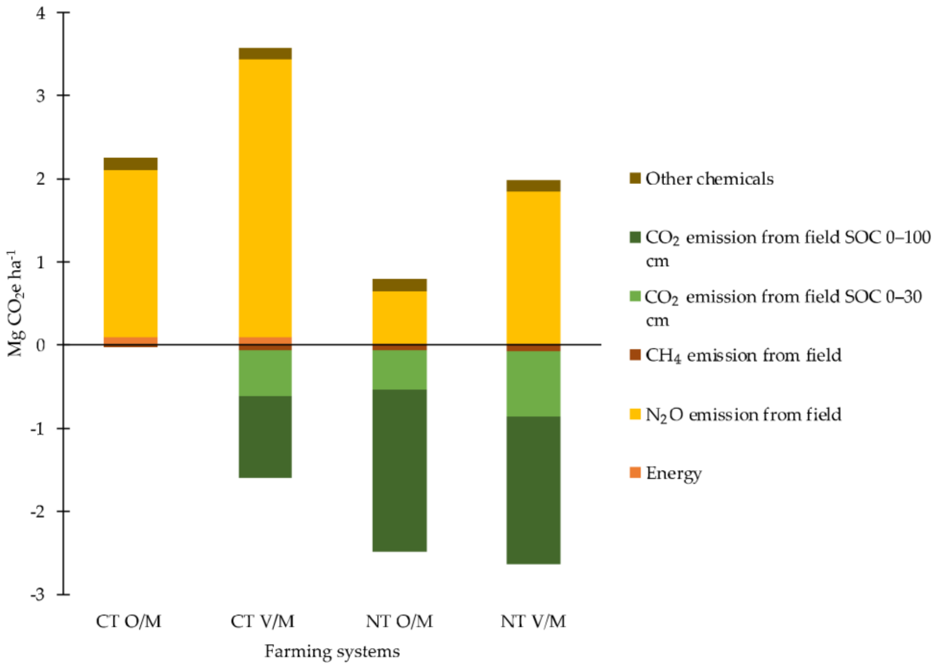

Figure 3. Life cycle GHG emissions per hectare from farming systems for each source. Net annual soil CO_2 emissions were calculated by taking annual soil C storage rates in farming systems in relation to CT O/M system (control).

The use of chemicals was the third source of GHG emissions to the atmosphere. Energy was the fourth source, responsible for 90.4 kg CO_2e ha^{-1} to CT and 12.2 kg CO_2e ha^{-1} to NT.

3.3. Net GHG Emissions from the Agroecosystems

We used measurements from two soil depths (0–30 cm and 0–100 cm) to estimate the SOC storage rate and corresponding CO_2 emissions in addition to emissions from other life cycle components (Figures 4 and 5). The results of the SOC storage rate at the soil layer depth of 0–30 cm with other life cycle components were from 0.3 to 3.0 Mg CO_2e ha^{-1} (Figure 5). The NT O/M farming systems had the lowest net GHG emissions intensity with 0.3 Mg CO_2e ha^{-1}, while the CT V/M had the highest emissions with 3.0 Mg CO_2e ha^{-1}. This analysis shows that the CT farming systems have more GHG emissions than NT farming. The GHG intensity by kg of maize showed that the NT systems were able to decrease GHG emissions by more than 70% compared to the use of the CT systems at the 0–30 cm depth.

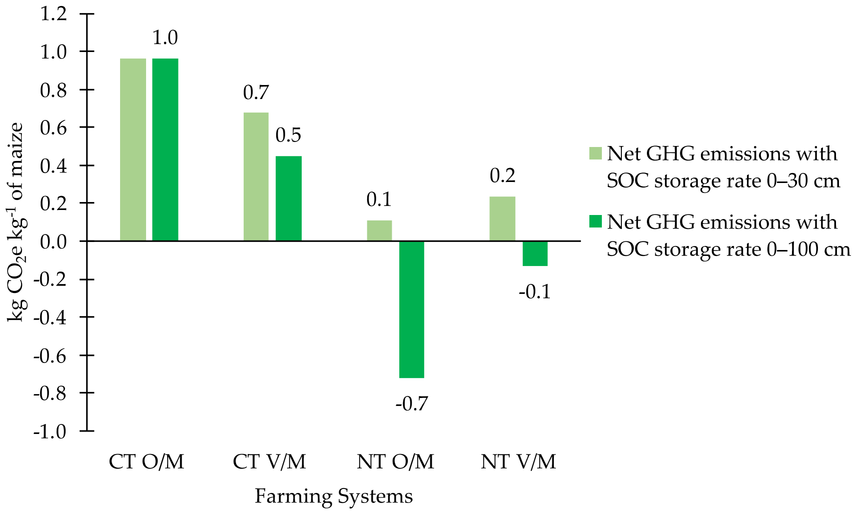

Figure 4. Life cycle GHG intensity per kg of maize for farming systems using two different C sequestration rates based on different depths.

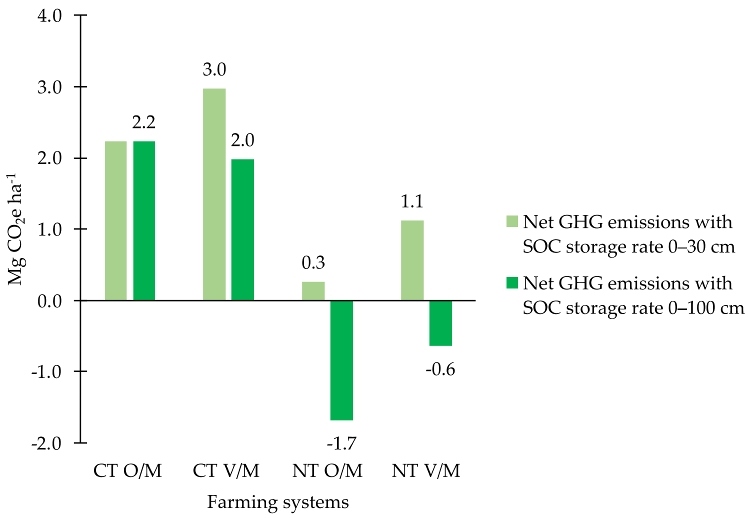

Figure 5. Life cycle GHG intensity per hectare of maize for farming systems using two different C sequestration rates based on different depths.

The SOC storage rates at the soil layer depth of 0–100 were also used to calculate emission values, and the life cycle emissions ranged from −1.7 to 2.2 Mg CO_2e ha^{-1} (Figure 5). The NT O/M farming systems had the lowest emissions with an average of −1.7 Mg CO_2e ha^{-1}, and the highest emissions were from the CT O/M system with 2.2 Mg CO_2e ha^{-1}. This analysis shows that the emissions per functional unit of one kg of grain amounted to 1.0 kg CO_2e in CT O/M (a positive GHG emission). The NT farming systems were able to mitigate their GHG emissions and showed negative emission values of −0.7 kg CO_2e in NT O/M and −0.1 kg CO_2e in NT V/M.

4. Discussion

Based on our measurements, the use of NT showed a greater efficiency in mitigating GHG emissions from maize production in southern Brazil compared to CT. The first change in GHG emissions is the use of diesel for agriculture operations, where NT was found to decrease diesel use by seven times compared to CT. A study by Vatsanidou et al. [51] found a reduction of 72% in fuel consumption for NT compared to CT. For each liter of fuel reduced in agricultural operations, GHG emissions can be reduced by 2.76 kg CO_2e per hectare [52]. According to Houshyar and Grundmann [53], cropping systems using conservation tillage are more energy efficient than conventional tillage, even if they have lower yields.

Legume cover crops increased agroecosystem efficiency in the use of resources due to increased maize yield, consequently reducing the GHG emissions per kg of maize because legume cover crops can provide nitrogen through biological nitrogen fixation. These benefits depend on the cropping system design. According to Nemecek et al. [54,55], cropping systems with crop rotation can improve their eco-efficiency by using a legume cover crop that can provide N for fertilization, which enables a reduction in N fertilizer applications. In this study, we found that the use of legume cover crops increased N_2O emissions from soil per hectare in legume cover crops compared to Gramineae; however, legume cover crops decreased N_2O emissions from the soil per kg of maize due to increased crop yield. In addition, using NT was found to decrease up to 45% N_2O emissions from soil per hectare and kg of maize compared to CT. These results are in line with those found by Fiorini et al. [56], who reported in their study a 51% reduction in N_2O emissions in NT compared with CT.

The Gramineae cover crop was more efficient in decreasing GHG emissions only for CH_4 when it had a higher CH_4 influx than the legume cover crop. Due to competition between NH_3 and CH_4 for methane monooxygenase enzymes, in an environment with high N available, CH_4 oxidation is slower or temporarily inhibited until N levels reduce [20,22,57–60].

This study showed that using data for C sequestration only in the superficial layer (0–30 cm depth) can lead to underestimating soil capacity for C sequestration compared to a depth of 0–100 cm. Some studies in Brazil found [24,61,62] that ~50% of C sequestration occurred in the layer from 0 to 30 cm and another ~50% in the layer from 30 to 100 cm. Using C sequestration to the depth soil layer (0–100 cm) proved that the use of NT provides mitigation of all GHG emissions compared to CT. Numerous studies globally have reported that conservation tillage methods support C sequestration, while CT leads to soil organic carbon decline and CO_2 released into the atmosphere [23,24,26,63–66]. When Holka and Bieńkowski [32] included soil C sequestration in their LCA, GHG emissions were reduced by 42.3% to 78.3% in CT and NT, respectively. The possibilities of GHG emission reduction resulted primarily from managing the maize crop residues and the cultivation of cover crops [32,67,68]. Veloso et al. [24] found that farming systems under NT with high crop residue inputs in southern Brazil sequestered 1.15 Mg ha^{-1} $year^{-1}$ to a soil layer of 0–100 cm. High crop residues in the field contributed to the mitigation of C losses and increased C sequestration [24]. Bayer et al. [27] found in an experiment in southern Brazil that the annual C addition required to maintain C stocks is 9 Mg C ha^{-1} yr^{-1} for CT and 4 Mg C ha^{-1} $year^{-1}$ for NT. In our study, NT O/M had the highest C sequestration rates per kg of maize. However, we must highlight that C sequestration per hectare by NT farming systems was nearly equal (Table 2), but the farming system that used legume cover crops had a maize yield twice that of NT O/M (Table 3). This resulted in a lower sequestration per kg of maize in NT V/M compared to NT O/M. Therefore, cropping systems can influence CO_2 and N_2O emissions by changing the quality and quantity of crop residue on the soil [24,51]. The higher quality of the legume cover crop residue may improve soil C sequestration potential conditions [41,69,70]. This study shows an improvement in C sequestration (0.7 Mg ha^{-1} yr^{-1}) and maize yield (4797 kg ha^{-1}) promoted by the legume cover crop.

NT farming systems had negative GHG intensities, but the NT O/M had nearly triple the amount of negative GHG intensity than NT V/M per hectare and seven times per kg of maize (Figures 4 and 5). On the other hand, the NT V/M had twice the yield of NT O/M. In this study, the GHG intensity in NT farming systems was negative, mitigating the whole GHG emissions from field and agriculture activities. In similar studies, maize cultivation in the United States under the NT system with a legume cover crop helped to reduce GHG emissions by 42% compared to CT [71]. Afshar and Dekamin [72] found GHG emissions in NT between 0.112 and 0.252 kg CO_2e kg^{-1} maize. In a study located in India [73], the adoption of NT reduced GHG emissions from maize production by 39% compared to the CT. The comparison among tillage in our analysis has shown that NT practices resulted in better environmental performance than CT in southern Brazil.

5. Conclusions

Our study shows how NT can mitigate ~50% of greenhouse gas emissions in comparison to conventional tillage in agricultural systems in southern Brazil without counting SOC storage rates. When including SOC storage rates at 0–30 and 0–100 cm, NT can mitigate from ~70% to 100% of GHG emissions, having a net negative GHG emission. The soil carbon sequestration found in NT has the capacity to offset all other GHG emissions in the agroecosystem, and the findings reinforce the importance of measuring C storage in deeper layers in tropical and subtropical soils. The use of legume cover crops increases soil N_2O emissions, but on the other hand, the productivity of the agricultural system increases, achieving greater efficiency in the use of resources.

Our results deserve attention because ~50% of the cropping area in Brazil is cultivated with grains, ~33 million hectares is under NT, and just over 20 million hectares is under maize. This study finds that much maize is under NT and is also produced with low GHG emissions. This study provides evidence that maize agriculture in Brazil can mitigate 100% of GHG emissions from agricultural activities. Thus, NT and using cover crops can help Brazil reduce its emissions and meet the goals of the 2015 Paris Agreement and the 2030 Agenda.

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