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Impact of Crop Type and Soil Characteristics on Greenhouse Gas Emissions in Latvian Agricultural Systems

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Abstract: This study investigates the impact of crop type and soil characteristics on greenhouse gas (GHG) emissions in Latvian agriculture, offering insights directly relevant to policymakers and practitioners focused on sustainable land management. From 2020 to 2023, emissions were monitored across four agricultural sites featuring different crop rotations: blueberry monoculture, continuous maize cropping, winter barley–winter rapeseed rotation, and spring barley–bean–winter wheat–fallow rotation. Results indicate that GHG emissions vary widely depending on crop and soil type. CO_2 emissions varied significantly based on both crop and soil type, with organic soils under maize cultivation in Mārupe averaging 184.91 kg CO_2 ha^{-1} day^{-1}, while mineral soils in Bērze under spring barley emitted 60.98 kg CO_2 ha^{-1} day^{-1}. Methane absorption was highest in well-aerated mineral soils, reaching 6.11 g CH_4 ha^{-1} day^{-1} in spring barley fields in Auce. Maize cultivation contributed the highest N_2O emissions, reaching 33.15 g N_2O ha^{-1} day^{-1}. These findings underscore that targeted practices, like optimized crop rotation and fertilizer use, can substantially reduce GHG emissions. Climate variability across locations affects soil moisture and temperature, but these factors were statistically controlled to isolate the impacts of crop type and soil characteristics on emissions. This study provides valuable data to inform sustainable agricultural policies and help achieve EU climate goals.

Keywords: GHG emissions; crop type; soil characteristics; agriculture

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1. Introduction

Reducing greenhouse gas (GHG) emissions is essential for mitigating climate change and promoting sustainable development for future generations. Soil management plays a vital role in this process, as soil health is essential not only for biodiversity but also for regulating water flow and nutrient cycling. To address these needs, the European Green Deal has set ambitious targets to reduce GHG emissions, aiming for climate neutrality across the European Union by 2050. As part of this initiative, the Zero Pollution Action Plan focuses on reducing pollution in water, air, and soil to levels that pose minimal health risks, thereby creating safer environmental conditions for both ecosystems and human populations [1,2].

Agricultural practices and soil-crop interactions significantly influence GHG emissions, with emissions varying based on factors such as soil organic matter, crop nitrogen requirements, and soil aeration. Soils emit key GHGs, including carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), with CO_2 being the largest contributor due to microbial respiration and organic matter decomposition [3,4]. Intensive land cultivation and rising temperatures deplete soil organic matter, compromising soil structure and fertility [4]. However, sustainable agricultural practices, such as optimized fertilizer use, reduced tillage, renewable energy adoption, and bio-based products, offer opportunities to reduce these emissions [5].

Methane dynamics in soils can vary significantly. For instance, in well-aerated mineral soils, methane can be absorbed and oxidized to CO_2 by methane-oxidizing bacteria, a process known as methanotrophy [6]. Studies have shown that incorporating crop residues (e.g., rice or maize), biochar, and nutrient management practices can reduce CH_4 emissions from soil [7]. In contrast, cultivated organic soils, especially those drained for agriculture, emit high levels of CO_2 and N_2O due to peat decomposition and fertilizer use. Even abandoned lands often continue to emit CO_2 from peat decomposition and maintain elevated N_2O emissions due to residual nitrogen from past agricultural practices [8]. Excessive nitrogen fertilizer use intensifies N_2O emissions through bacterial nitrification and denitrification, especially in crops with high nitrogen demands, such as maize, wheat, rice, and barley [9]. Determining optimal nitrogen application rates is essential to balance emissions reduction with crop productivity. Additionally, abandoned croplands represent a promising opportunity for GHG mitigation when managed properly. Strategies such as natural regrowth, afforestation, and bioenergy crop cultivation could sequester up to 4.0 Gt CO_2 equivalent annually by 2050, contributing to climate goals through enhanced carbon sequestration and improved soil health [10]. Crops affect soil microbiology by releasing organic compounds through their roots, which feed soil microorganisms. The decomposition of organic matter by these microorganisms results in CO_2 emissions, while nitrogen fertilizers amplify microbial activity and soil respiration, further increasing GHG emissions [11].

This study aims to assess and analyze GHG emissions from representative agricultural sites in Latvia. By examining emissions from soils supporting various crop types, this study seeks to quantify and compare the GHG emission levels associated with common crops in the region. These findings will provide insight into how crop choice and management practices impact soil GHG emissions, contributing valuable information for sustainable agriculture and climate mitigation strategies.

2. Materials and Methods

The amount of GHG emissions from the soil was measured at research sites in Laflora, Auce, Mārupe, and Bērze. The Laflora site is located in the Kaigu peat bog (56.711413° N, 23.604287° E), characterized by organic soil where blueberries (*Vaccinium corymbosum*) are cultivated. The pH values in this area range from 3.9 to 4.3, with organic matter content ranging from 65.0% to 82.7% and nitrate (NO_3) levels from 0.4 mg/kg to 200.8 mg/kg. This site belongs to SIA "Arosa-R", which specializes in cultivating blueberries and imports seedlings from U.S. nurseries, adapting them to Latvia's climate. SIA "Arosa-R" ensures that the soil is similar to that of pine forests where wild blueberries grow, providing optimal conditions for blueberry growth [12]. The Auce research site is located at 56.493879° N, 22.979399° E. According to the soil classification, this site features *Gleyic Cambisol* soil, with pH values ranging from 7.1 to 7.8, organic matter content between 1.8% and 2.6%, and NO_3 levels ranging from 2.8 mg/kg to 33.2 mg/kg. The Mārupe research site, located at 56.8536442° N, 23.9480304° E, is characterized by organic soil where maize (*Zea mays*) is predominantly grown. The pH values here range from 5.4 to 7.1, with organic matter content between 11.1% and 37.5% and NO_3 levels between 10.9 mg/kg and 133.9 mg/kg. The Bērze site is located in Dobele municipality, in the Zemgale Plain of the Central Latvian lowland (56.713871° N, 23.376573° E). This area contains mineral soils classified as *Calcic Cambisol*, with pH values ranging from 6.8 to 7.8, organic matter content between 3.3% and 4.4%, and NO_3 levels ranging from 2.7 mg/kg to 57.7 mg/kg.

The intensity of cropping systems varies across sites, with Auce showing moderate nitrogen input in a crop rotation system involving winter barley, rapeseed, and wheat; Bērze utilizing low nitrogen input in a crop-fallow rotation with spring barley, field beans, and winter wheat; Laflora focusing on continuous blueberry cultivation with no nitrogen input and very high organic matter; and Mārupe showing high nitrogen demand in an annual crop rotation system, predominantly with maize. The characteristics of the study sites are shown in Table 1.

Table 1. Characteristics of study sites from 2020 to 2023.

Site	Year	pH	Organic Matter, %	N-NO_3, mg/kg	Crop	Nitrogen Input, kg N ha^{-1}
Auce	2020	7.1	2.3	33.2	Winter barley *(Hordeum vulgare)*	150.8
	2021	7.3	2.4	15.5	Winter rapeseed (*Brassica napus*)	179.8
	2022	7.5	2.0	9.4	Winter wheat (*Triticum aestivum*)	139.2
	2023	7.7	2.4	17.2	Winter barley (*Hordeum vulgare*)	106.0
Bērze	2020	6.8	3.9	23.4	Spring barley (*Hordeum vulgare*)	45.2
	2021	7.4	3.7	34.1	Field beans (*Vicia faba*)	14.2
	2022	7.4	3.9	5.2	Winter wheat (*Triticum aestivum*)	125.9
	2023	7.4	4.3	5.9	Fallow (poor germination of spring barley)	17.6
Laflora	2020	3.9	77.8	0.4	Blueberry (*Vaccinium corymbosum*)	63.8
	2021	4.0	77.1	100.6	Blueberry (*Vaccinium corymbosum*)	63.8
	2022	4.2	76.9	16.3	Blueberry (*Vaccinium corymbosum*)	63.8
	2023	4.2	70.9	3.6	Blueberry (*Vaccinium corymbosum*)	63.8
Mārupe	2020	5.4	37.5	133.8	Maize (*Zea mays*)	145.0
	2021	6.2	24.9	125.7	Maize (*Zea mays*)	145.0
	2022	6.7	18.9	45.2	Maize (*Zea mays*)	145.0
	2023	6.9	12.9	11.0	Rye (*Secale cereale*)	60.0

GHG emissions were measured approximately every two weeks throughout the vegetation period, from April to October. Between 2020 and 2023, precipitation at the Mārupe measurement site ranged from 316.9 mm to 434.9 mm, while at the Auce, Bērze, and Laflora measurement sites, it was slightly lower, ranging from 340.9 mm to 368.1 mm. Air temperature at all locations was similar, varying from 12.99 °C to 14.16 °C. Using the Picarro G2508 gas analyzer (Picarro, Santa Clara, CA, USA) (Figure 1), which employs cavity ring-down spectroscopy technology, the instrument ensures outstanding long-term stability by precisely controlling cavity temperature, pressure, and frequency, thereby minimizing calibration requirements [13]. Comprehensive calibration and maintenance by a certified Picarro engineer are conducted every two years to ensure sustained measurement accuracy. To ensure consistent measurements, the device was preheated to 45 °C. Three chambers were placed in the soil at a depth of 4 cm for measurement, with each chamber monitored for 240 s. The device is capable of simultaneously measuring five gases: N_2O, CH_4, CO_2, NH_3, and H_2O. At the start of each measurement, a data logger (Driver DL 500, Eijkelkamp) was inserted into the chamber to record the air temperature and atmospheric pressure inside the chamber.

Gas measurements were conducted using a non-transparent chamber with a base diameter of 23 cm and a volume of 3 L (Figure 2). The chamber's base ring is made of metal, with a sharpened lower edge to facilitate insertion into the soil. The inserted ring has a rubber gasket around the top, allowing the chamber's dome to be securely connected to the base ring. The dome of the chamber is connected to the Picarro G2508 analyzer via a stainless-steel connector, which is linked to a 9-m-long Teflon tube. The outer diameter of the tube is 3.175 mm, and the inner diameter is 1.587 mm. In total, 475 measurements were performed during the study period. To calculate emissions from the concentration data, the Soil Flux Processor (SFP) from Picarro Inc. was used, which calculates emissions based on a linear model [14]. The data from the SFP were then converted to grams or kilograms per hectare per year. The emission coefficient conversion to concentration per day per hectare was based on the ideal gas law. When performing these transformations, it is crucial to maintain a consistent system of units. The Picarro G2508 measures gas molar concentrations, so a conversion from molar concentration to mass concentration was carried out.

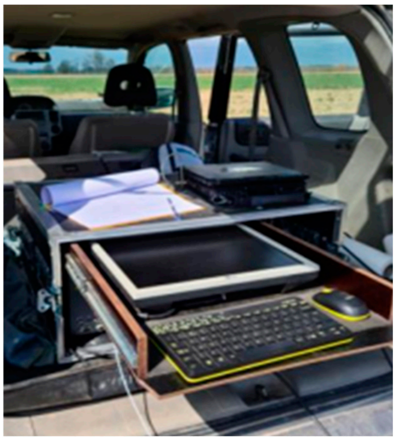

Figure 1. Picarro G2508.

Figure 2. Chamber and three rings used for measurement.

To ensure data quality and accuracy, thorough data processing steps were performed, including data cleaning and normalization. Data cleaning involved a careful review to identify outliers and any inconsistencies. Any significant gaps were excluded to maintain data reliability. Outliers were visually inspected, and clearly erroneous values caused by measurement errors were removed to ensure accuracy. Normalization was applied to standardize emissions data across different study sites and cropping systems [15]. This process enabled meaningful comparisons by focusing on differences in emissions related to crop and soil type.

Once the data were processed, it was compiled into a dataset for further analysis using JASP (Jeffreys's Amazing Statistics Program) software. JASP, a free software program similar to SPSS, was used to conduct the statistical analysis. The Shapiro-Wilk test, calculated by JASP, was used to check for normal data distribution. The statistical analysis methods used are summarized in Table 2.

Since the data did not meet the assumptions of normal distribution, non-parametric methods were deemed appropriate. As a result, the Kruskal–Wallis test was employed, which is suitable for comparing more than two independent groups with non-normally distributed data. Differences in GHG emissions among various crops were visualized in graphs using RStudio version 4.4.1, which provides accurate visualizations and a wide range of statistical analysis options. The resulting data distributions were further examined through boxplots (Figure 3).

Table 2. Summary of statistical methods and software used for analysis.

Statistical Analysis	Examined	Software
Shapiro–Wilk test	Normality of the measured data distribution	JASP
Kruskal–Wallis test	Statistical differences of N_2O, CO_2, CH_4 emissions between sites	JASP
Mann–Whitney test	Statistical differences of N_2O, CO_2, CH_4 emissions between soil types	SPSS
Analysis of Variance (ANOVA)	The impact of crops on GHG emissions	RStudio 4.4.1

Figure 3. Boxplot explanation: dots represent individual data points. The box shows an interquartile range (middle 50%), with the median as a black line and the mean as a red diamond. Whiskers indicate the minimum and maximum values.

To compare the climate impact of each crop type, Global Warming Potential (GWP) was calculated using emissions data processed in RStudio. These calculations allow for a more integrated assessment of GHG emissions across crop types, enabling clear insights into each crop's contribution to climate impact relative to its productivity.

To calculate the annual GWP for each crop, average emissions data for CO_2, N_2O, and CH_4 were used. N_2O and CH_4 emissions were converted into CO_2 equivalents using IPCC GWP factors of 298 for N_2O and 25 for CH_4, allowing for comparison based on climate impact. Then, CO_2 equivalent values of N_2O and CH_4 were added to CO_2 emissions to obtain a total GWP per hectare. This average GWP value was then scaled to an annual basis by multiplying by 365, providing an estimate of the yearly emissions in CO_2 equivalents per hectare. This calculation yielded a standardized measure of each crop's annual climate impact in terms of CO_2 equivalents.

3. Results and Discussion

3.1. CO_2 Emissions

From Figure 4, annual CO_2 emissions varied notably by site and crop type ($p < 0.05$). In organic soils under maize cultivation at Mārupe, CO_2 emissions increased steadily each year, rising from 139.18 kg CO_2 ha^{-1} day^{-1} in 2020 to 200.05 kg CO_2 ha^{-1} day^{-1} in 2022. This increase can be attributed to the cumulative effects of organic matter decomposition and sustained microbial activity in these nutrient-rich soils [4]. Organic matter serves as a critical carbon source for microbial activity, while vegetation type significantly influences CO_2 emissions through variations in root structures, biomass, and nutrient demands. For instance, high-biomass crops like maize can support extensive microbial communities by providing root exudates, which, in turn, promote higher CO_2 emissions [4]. At the Laflora measurement site, however, CO_2 emissions remained more stable throughout the year, with a notable decrease in 2023. This reduction may be explained by increased air temperature compared to previous years.

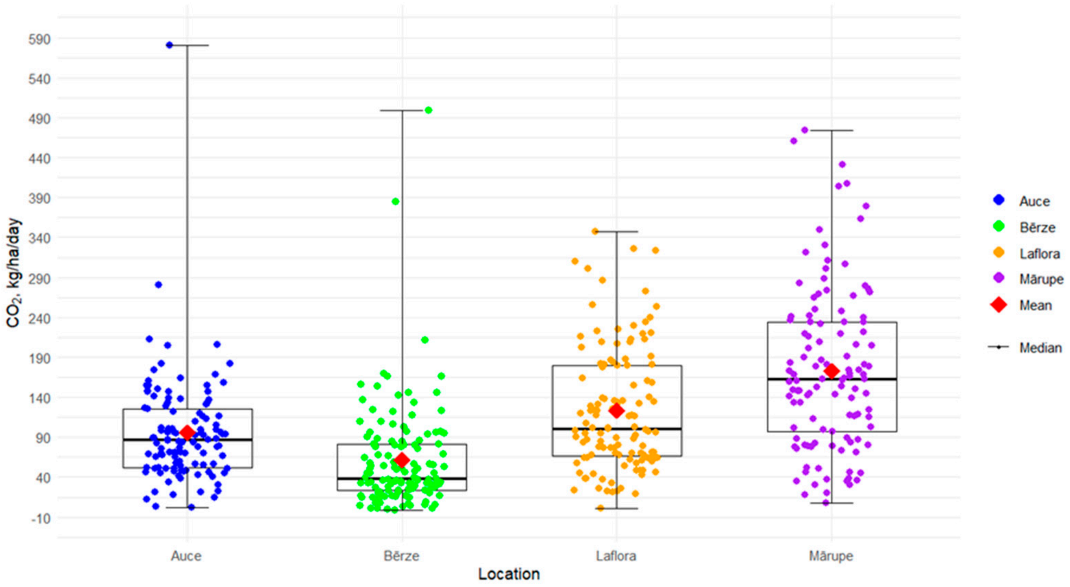

Figure 4. CO_2 emission levels based on the study location.

In mineral soils at Bērze, CO_2 emissions remained relatively stable over the years, averaging approximately 61.43 kg ha^{-1} day^{-1}. The lower organic content in mineral soils limits the availability of microbial substrates, resulting in consistently lower emissions compared to organic soils. Well-aerated soils enhance microbial activity by accelerating organic matter decomposition, leading to higher CO_2 release [16]. Conversely, compacted or poorly drained soils with limited aeration can create anaerobic conditions, which slow decomposition and reduce CO_2 emissions [17].

This pattern suggests that mineral soils, particularly under low-input crops like barley, contribute less to annual CO_2 emissions than organic soils under high-input crops. Considering factors such as organic matter content, vegetation type, and soil aeration offers a more integrated understanding of the drivers behind CO_2 emission differences observed across locations.

3.2. N_2O Emissions

Statistically higher N_2O emissions were observed in organic soils compared to mineral soils ($p < 0.05$). The high N_2O emissions observed at Mārupe during maize cultivation in 2021, reaching 88.04 g N_2O ha^{-1} day^{-1}, likely reflect the interaction between the high organic content in the soil and the high nitrogen demand of maize (Figure 5). Organic soils, with their high organic matter, can enhance nitrogen availability, especially under nitrogen-intensive crops like maize. Previous studies have shown that nitrogen-rich soils, particularly those with high organic matter content, create an environment conducive to microbial processes such as nitrification and denitrification, both of which produce N_2O [18]. In contrast, N_2O emissions at Laflora declined steadily from 9.29 kg N_2O ha^{-1} day^{-1} in 2020 to 1.03 kg N_2O ha^{-1} day^{-1} in 2023 during blueberry cultivation. This suggests that perennial crops, such as blueberries, may stabilize nitrogen dynamics and reduce emissions over time in organic soils. Additionally, the relatively high emissions from field beans at Bērze in 2021 (11.56 kg N_2O ha^{-1} day^{-1}) highlight how nitrogen-fixing crops can further elevate soil nitrogen levels in both organic and mineral soils. These observations emphasize the strong influence of crop type, soil organic matter, and nitrogen management on N_2O emissions in agricultural systems.

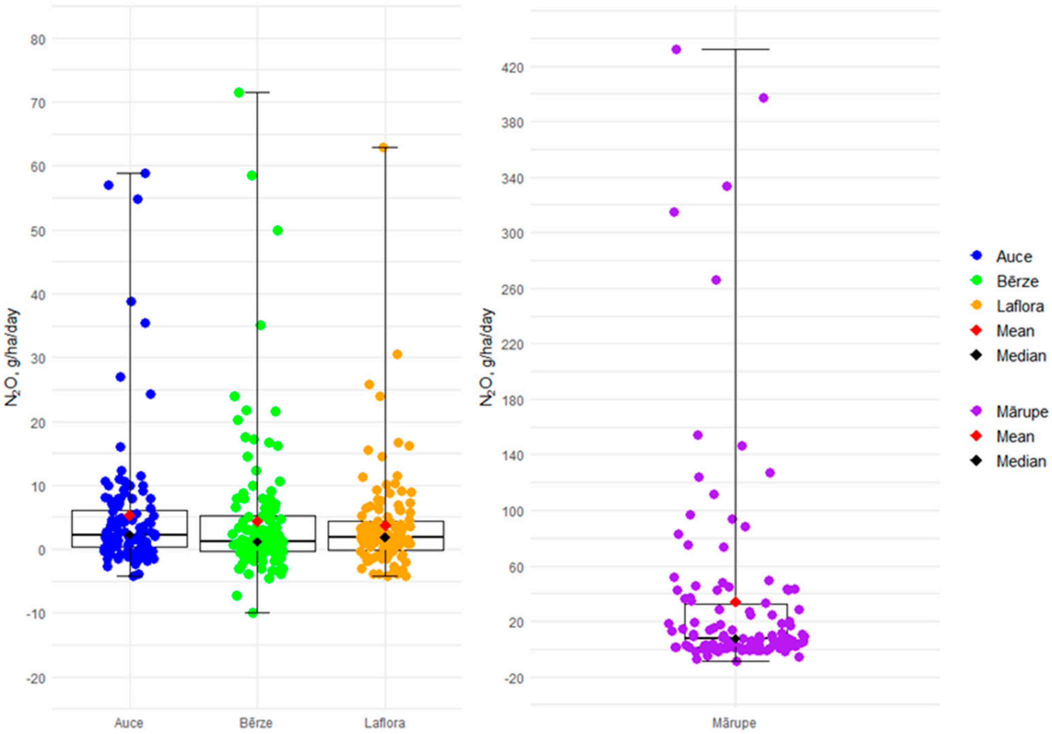

Figure 5. N_2O emission levels are based on the study location.

3.3. *CH_4 Emissions*

CH_4 emissions displayed notable trends over the years, with both mineral and organic soils acting as CH_4 sinks across all sites. As shown in Figure 6, the mineral soils of Auce demonstrated a higher average CH_4 assimilation rate compared to those at Bērze (3.98 and 0.69 g CH_4 ha^{-1} day^{-1}, respectively). When comparing mineral soils with organic soils, the organic soils showed a higher average CH_4 assimilation rate ($p < 0.05$), with the highest value recorded in 2024 at the Mārupe measurement site, where rye was cultivated. This observation is consistent with the findings of Oertel et al. (2016), which state that soils with higher organic matter content demonstrate greater CH_4 uptake [3]. At Mārupe, CH_4 assimilation rates increased over time, from 3.46 g CH_4 ha^{-1} day^{-1} in 2020 to 4.58 g CH_4 ha^{-1} day^{-1} in 2023. This trend suggests that the aeration capacity of soil and microbial oxidation potential improved over time, supporting increased CH_4 uptake. Well-aerated soils favor methane oxidation by supporting methanotrophic bacteria, making well-aerated soils effective CH_4 sinks [17,19].

In contrast, the mineral soils at the Bērze monitoring site consistently showed lower CH_4 absorption rates, decreasing from 0.37 g CH_4 ha^{-1} day^{-1} in 2020 to 0.68 g CH_4 ha^{-1} day^{-1} in 2023. This decline is likely attributed to reduced tillage practices observed over the years. Additionally, the higher moisture content in these soils limits oxygen availability, which is critical for the survival and activity of methanotrophic bacteria. Moisture-rich soils are less effective CH_4 sinks due to reduced oxygen diffusion [20].

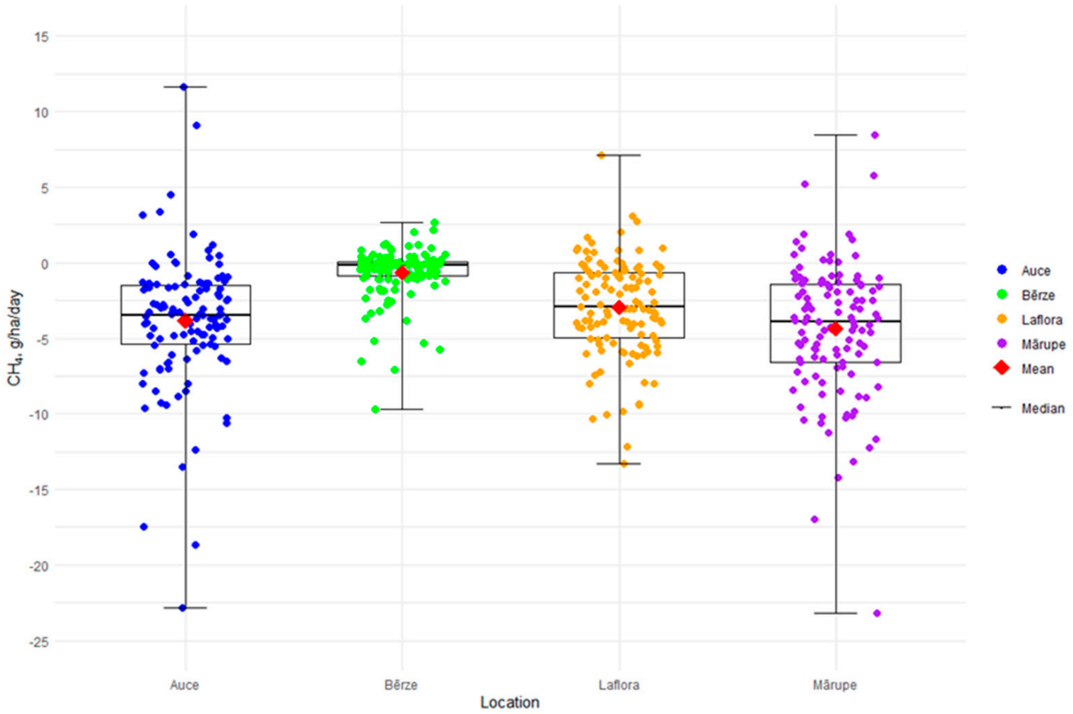

Figure 6. CH_4 emission levels based on the study location.

3.4. Effect of Crop Type

The violin boxplots illustrate the differences in GHG emissions based on the cultivated crops (Figure 7). High-emission crops, like rye and maize, showed the greatest contributions to N_2O and CO_2 emissions, averaging 37.33 g N_2O ha^{-1} day^{-1} and 184.91 kg CO_2 ha^{-1} day^{-1}, respectively. These high emissions are primarily attributed to the substantial nitrogen inputs and intensive microbial activity associated with these crops, especially in nutrient-rich organic soils [3,21].

In contrast, crops such as winter rapeseed and fallow systems (which included poorly germinated spring barley with an initial fertilization dose) demonstrated significantly lower emissions. Fallow land emitted 12.7 t CO_2 equivalents ha^{-1} $year^{-1}$, suggesting that minimal vegetation and nitrogen application reduced emissions compared to active cropping systems. Methane dynamics also varied, with all crop types showing net CH_4 absorption. Winter rapeseed (-6.11 g CH_4 ha^{-1} day^{-1}) and rye (-4.58 g CH_4 ha^{-1} day^{-1}) were the most effective CH_4 sinks. Table 3 provides a comparison of the annual GWP for each crop, showing their total climate impact per hectare over a year based on average CO_2, N_2O, and CH_4 emissions from soil.

Table 3. Summary of GWP for different crops in Latvia.

Crop	Annual GWP (t CO_2 Equivalents ha^{-1} $year^{-1}$)
Blueberry	45.3
Maize	71.1
Fallow	12.7
Field beans	28.4
Rye	56.3
Spring barley	22.8
Winter wheat	34.1
Winter barley	33.1
Winter rapeseed	32.7

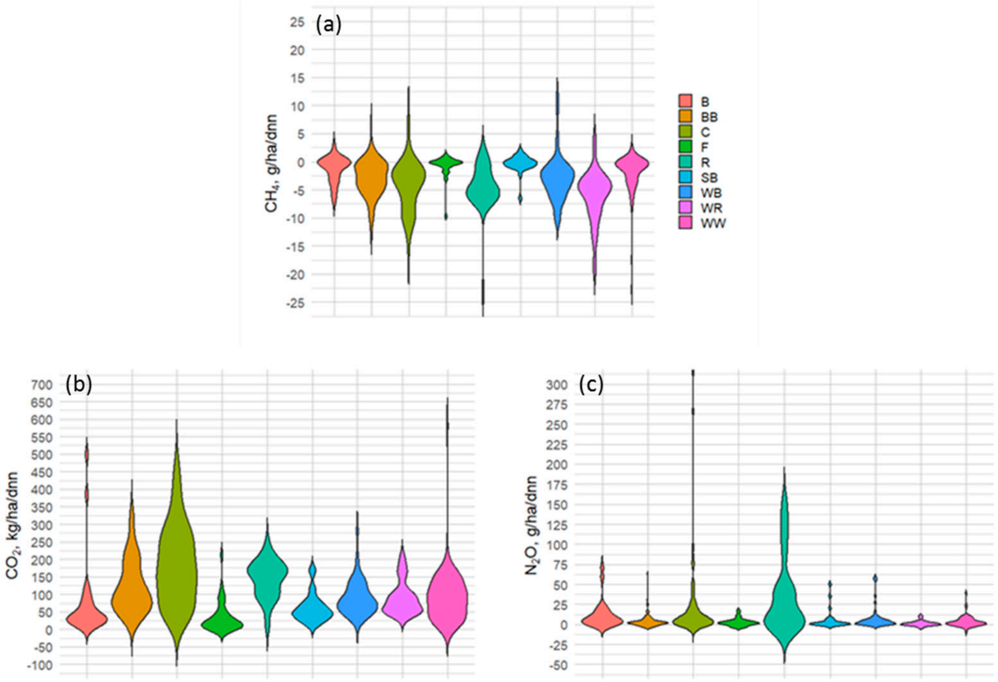

Figure 7. Emission levels of (**a**) CH_4, (**b**) CO_2, and (**c**) N_2O based on the cultivated crop. Abbreviations: WW, winter wheat; WR, winter rapeseed; WB, winter barley; SB, spring barley; R, rye; F, fallow; C, maize; BB, blueberry; B, field beans.

These findings highlight the critical role of crop selection and management in regulating GHG emissions from soil, emphasizing the need for strategies that align crop type with soil conditions and sustainability goals to mitigate agricultural climate impacts.

3.5. Limitations and Implications for Sustainable Agriculture

The data on GHG emissions reveal notable differences across various Latvian agricultural sites, with soil type playing a crucial role in shaping CO_2, N_2O, and CH_4 emission levels. By analyzing emissions from both organic and mineral soils, we observe distinct patterns in the behavior of each GHG based on soil properties and crop type. The progressive increase in CO_2 emissions in organic soils suggests a potential need for modified crop rotation or reduced tillage practices to limit cumulative CO_2 release. This could be particularly beneficial in high-input systems, where continuous organic matter addition increases CO_2 emissions over time [16]. The variability in N_2O emissions underscores the importance of precise nitrogen management, especially for high-nitrogen-demand crops like maize. Adjusting nitrogen application rates based on crop requirements and soil conditions could stabilize N_2O emissions and reduce annual spikes in wetter years, aligning with strategies outlined by Demone et al. [9]. Similarly, the year-over-year increase in CH_4 uptake in agricultural soils highlights their potential to act as methane sinks under proper management. Seasonal changes in CH_4 assimilation rates, which typically increase during warmer, drier periods due to improved soil aeration, further emphasize the importance of soil management practices [22].

However, the analysis focused exclusively on emissions from soils, without addressing contributions from biomass production, transportation, and other indirect sources, thereby limiting the scope of the findings. Additionally, meteorological parameters such as air temperature, precipitation, and soil moisture regime, which significantly affect soil properties and microbial processes, were not explicitly included [3]. Given the variability in GHG emissions influenced by year-to-year weather differences, this limitation is significant. For instance, warmer, drier seasons tend to reduce N_2O emissions and enhance CH_4 uptake in conventionally tilled systems, whereas cooler, wetter conditions increase N_2O emissions under reduced tillage [23].

Despite these limitations, the results underscore the importance of tailored strategies in sustainable agriculture to mitigate climate impacts. Future research should focus on the benefits of crop rotations and mixed cropping systems in mitigating emissions, along with the interplay between crop type, tillage method, and seasonal meteorological conditions, integrating life-cycle assessments to provide a comprehensive view of agricultural emissions. By doing so, it will be possible to develop adaptive, site-specific management practices that align with broader climate goals.

4. Conclusions

This study highlights the significant influence of crop types and soil characteristics on greenhouse gas (GHG) emissions in Latvian agriculture. The findings suggest that nitrogen-intensive crops, such as maize grown on organic soils, tend to result in higher CO_2 and N_2O emissions, underscoring the need for careful nitrogen management and strategic crop selection to mitigate emissions. Conversely, mineral soils, particularly when well-aerated, demonstrate the potential to act as methane sinks, absorbing methane and contributing to emission reductions. These results emphasize the importance of tailoring agricultural practices to specific soil types and environmental conditions.

Practical strategies, such as optimizing nitrogen inputs in organic soils and enhancing aeration in mineral soils, offer promising paths for reducing the environmental impact of farming. By adopting these approaches, agriculture can play a key role in achieving sustainability targets, including those outlined in the European Green Deal.

Future research should focus on the potential benefits of crop rotations and mixed cropping systems in mitigating GHG emissions, as well as explore seasonal variations and their interactions with soil management practices. These studies are likely to provide valuable insights into how long-term agricultural practices can be refined to meet climate objectives, supporting a more sustainable agricultural system.

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