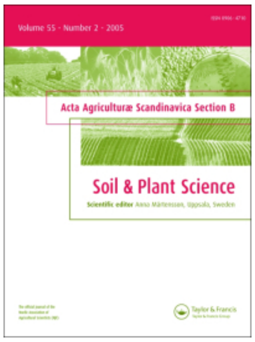

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RESEARCH ARTICLE

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Soil tillage and agricultural crops affect greenhouse gas emissions from *Cambic Calcisol* in a temperate climate

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ABSTRACT
Conventional soil tillage creates suitable conditions for plant growth, but it is an energy and labor-intensive technology causing ecologically unfavorable changes in the soil. In order to reduce GHG emissions from agricultural soils, reduced soil tillage and different crops have been proposed. However, the impact of individual practices on GHG emissions is affected by multiple on-site variables and is limited to different soil types and climate zones. Therefore, the aim of this study is to investigate the impact of two soil tillage treatments and four agricultural crops on GHG emissions from clay soil in temperate climate. During the growing seasons from 2018 to 2021, we measured soil flux of N_2O, CH_4 and CO_2 using a Picarro G2508 on a broad multifaceted field experiment with two tillage treatments. This study shows that winter wheat with conventional tillage treatment may emit significantly lower N_2O emission (8.3 g ha^{-1} day^{-1}) and higher CH_4 assimilation (−11.9 g ha^{-1} day^{-1}) in warmer and drier growing season compared to winter wheat (26.1 g ha^{-1} day^{-1} and −3.3 CH_4 g ha^{-1} day^{-1}, respectively) and spring barley (11.1 g ha^{-1} day^{-1} and −2.9 g ha^{-1} day^{-1}, respectively) with reduced tillage treatment in cooler and wetter growing season ($p<0.05$).

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KEYWORDS
Picarro G2508; conventional tillage; reduced tillage; winter wheat; winter rapeseed; spring barley; field beans

Introduction

Anthropogenic activities increase greenhouse gas concentrations in atmosphere globally. Warming effects from the three primary greenhouse gases (GHG) persist over a long period of time affecting both present and future generations. Carbon dioxide (CO_2) is the dominant GHG because its lifetime in the atmosphere is hundreds of years. Methane (CH_4) has a 21 times higher 100-year global warming potential than CO_2, and it stays in the atmosphere for about 12 years. The 100-year global warming potential for nitrous oxide (N_2O) is 298 times higher than for CO_2 and its lifetime in the atmosphere is about 114 years (IPCC, 2007).

The main sources of GHG emissions from the agricultural sector are CH_4 from enteric fermentation, CH_4 and N_2O from manure management, and CO_2 and N_2O from soil management. GHG emissions from soil depend on soil water content, soil temperature, availability of nutrients and land use (Oertel et al. 2016). The main global challenge is the need to simultaneously meet the demand for high-quality food and fibre and to reduce GHG emissions. In order to reduce GHG emissions from agricultural soils and their negative impact on global warming, it is necessary to introduce agricultural practices that would facilitate sustainable land management (Valujeva et al. 2020).

Soil tillage is one of the most important agricultural practices used to create suitable conditions for seedbed preparation and plant growth. In conventional tillage systems, the soil surface is inverted followed by one or two harrowing to create a suitable layer for plants (Abdalla et al. 2013), as a result increasing decomposition of organic matter and reducing the stock of soil organic carbon. Conventional tillage is energy and labour-intensive technology causing ecologically unfavourable changes in the soil (Amini and Asoodar 2015). There is a growing interest in environmentally-friendly tillage systems, which not only reduce the use of energy resources, but also improve the soil quality and reduce GHG emissions from the

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soil. Conservation tillage is based on reducing soil disturbance and incorporating crop residues to a soil management by limiting tillage to a shallow depth and preventing soil surface inversion (Abdalla et al. 2013). There are several conservation tillage types: no-tillage, mulch tillage, strip or zonal tillage, ridge tillage and reduced or minimum tillage (Busari et al. 2015; Opara-Nadi 1993). Mostly the minimum tillage is used to reduce the risk of soil erosion, but there are other positive benefits: improved nutrient cycling, improved soil moisture retention, the ability to reduce GHG emissions (Ogle et al. 2019) and increased soil aggregate stability (Steponavičienė et al. 2020). A period of more than 10 years is necessary to fully assess the effect of no-tillage technology on GHG emissions from soil (Cusser et al. 2020; Van Kessel et al. 2013). GHG flux from soil is increased by tillage (Peterson et al. 2019). Soil tillage increases respiration of soil microorganisms and increases CO_2 emissions from soil. As the tillage depth increases, CO_2 emission from soil significantly increases, therefore it is assumed that CO_2 emission from soil decreases by reducing the depth of tillage (Reicosky and Archer 2007). In contrast, N_2O emission is higher for conservation tillage (Badagliacca et al. 2018; Mei et al. 2018), but the results are inconclusive, because some scientists claim that the increase in N_2O emission is insignificant or that there is no difference at all (Abdalla et al. 2013). Soil can be both a source of CH_4 emission and an assimilator of CH_4. It is also assumed that no-tillage technology reduces CH_4 emission from soil, but no significant differences have been identified (Abdalla et al. 2013). CH_4 emission from soils is mainly related to wet soils (soil water content above 60%), but CH_4 assimilation occurs in drier soils where carbon is needed for biomass production. Tillage reduces the ability of soil to assimilate CH_4 when compared to before tillage (Peterson et al. 2019).

Agriculture can also contribute to climate change mitigation. In the context of the European Green Deal, policy makers seek for support mechanisms that could be provided to farmers to minimise GHG emissions and meet the demand for food. Before introducing support mechanisms, it is necessary to understand which management practices reduce GHG emissions in the relevant soil and climatic conditions. GHG emissions from agricultural land is a complex topic that has not been studied much as it depends on climate, soil type and management. Reduction in fertiliser application, reduced tillage depth and introduction of crop rotation may reduce GHG emissions from agricultural land. The main methods to reduce GHG emissions from the agricultural land management are such management practices as fertiliser application, tillage treatments and crop rotation. Reduction in fertiliser use, reduced tillage intensity and introduction of crop rotation may reduce GHG emissions from agricultural land (Oertel et al. 2016). By sowing legumes in rotation with cereals, crop rotation can reduce GHG emissions (Plaza-Bonilla et al. 2018) while also improving carbon (C) sequestration (Poeplau et al. 2015). For instance, the demand for N fertiliser decreases without reducing yield or grain quality (Plaza-Bonilla et al. 2017). Inclusion of winter rapeseed in crop rotation can reduce the risk of spreading plant pathogens and can reduce the use of pesticides (Vinzent et al. 2017). However, the studies of the impact of individual practices such as tillage and crops on GHG emissions are limited to different soil types and climate zones. Therefore, the aim of this study is to investigate the impact of two soil tillage treatments and four agricultural crops on GHG emissions from a clay soil in temperate climate. Based on the information mentioned above, it was hypothesised that reduced tillage and legumes can decrease GHG emissions from clay soil in temperate climate.

Materials and methods

Measurement site

This study was conducted at the Research and Study farm Peterlauki of Latvia University of Life Sciences and Technologies (56°30.658′N and 23°41.580′E) located in the central part of Latvia, Northern Europe (Figure 1).

The study was conducted on a broad multifaceted field experiment established in 2009 with two tillage treatments: conventional soil tillage (CT) with mouldboard ploughing at a depth of 22–24 cm and reduced soil tillage (RT) with disc harrowing up to a depth of 10 cm. The soil at the experimental field was a *Cambic Calcisol* (IUSS Working Group WRB 2015), neutral reaction, high in organic matter content, medium in phosphorus and high in potassium content (Table 1). The soil at the experimental field had a silty clay texture.

The experimental field consists of 4 pairs of plots, with a total number of 8 plots, the size of each plot – 24 × 100 m and area of each plot is 0.25 ha (Bankina et al. 2019; Dubova et al. 2016). The plots are located close to one another in flat terrain with homogeneous soil to minimise the effect of spatial variability on the study results. Agronomic measures for each pair were applied uniformly based on the agronomic requirements of intensive crop production. The use of synthetic fertilisers depend on the crop type, so the crop is used as a factor, which includes the fertilisation application time, amount and other crop specific measures. Detailed

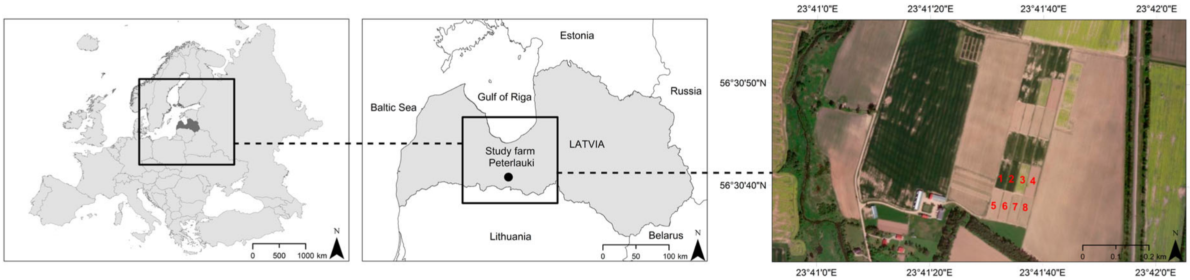

Figure 1. The location of the study site: red numbers – plots where the measurements were performed.

description of fertilisers used is given in Table S1 of the Supplementary Material. During the growing seasons (April to October) of 2018, 2019, 2020 and 2021, the soil flux measurements of N_2O, CH_4 and CO_2 were conducted every two weeks from 10AM to 2PM. The overview of the plots where GHG measurements were performed is given in Table 2.

Weather conditions

Latvia lies in the humid continental, no dry season, warm summer climate zone (Dfb) (Kottel et al. 2006). According to IPCC guidelines, which describe the classification of climate zones and the methodology for assessing national GHG emissions, Latvia is located in a cool temperate moist climate zone (IPCC 2019). The average annual air temperature was +6.8°C and the annual precipitation 686 mm (LVĢMCa n.d.). Publicly available weather data from the 'Latvian Environment, Geology and Meteorology Centre' meteorological observation station 'Jelgava' (56° 33′24.954″ N and 23°57′50.679″E) were used; the average air temperature of 2018 was +14.9°C, in 2019, 2020 and 2021 it was +13.6°C, +13.3°C and +13.4°C, respectively (LVĢMCb n.d.). Precipitation during the growing seasons of 2018, 2019, 2020 and 2021 was 337, 374, 434 and 358 mm, respectively (Figure 2).

Measurement of GHG fluxes and soil water content

Agricultural soil flux measurements of N_2O, CH_4 and CO_2 were performed using a mobile spectrophotometer Picarro G2508 (https://www.picarro.com/g2508_gas_concentration_analyzer), which allows to measure soil flux of N_2O, CH_4 and CO_2 simultaneously with an interval of one second between measurements. Soil flux of N_2O, CH_4 and CO_2 were measured three times in each study plot in different locations using non-transparent chambers with a diameter of 23 cm and volume of 3 l. The chamber consists of a metal base with a sharpened lower edge for easier installation in the soil, non-transparent dome and sealing rubber between the base and the dome to ensure a tight connection. The chamber was connected to Picarro G2508 using manufactured stainless-steel connector, 9 m long Teflon tube with outer diameter of 3.175 mm and inner diameter of 1.587 mm, and quick connector insulated with a rubber seal (Valujeva et al. 2017). The metal base was installed 30 min before the start of the measurement and the non-transparent dome was laid on the base and connected to Picarro G2508 just before the start of measurement. The total number of measurements was 460, time of each measurement time 400 s.

All flux rates were determined according to linear model (Wagner et al. 1997) used by Soil Flux Processor (SFP) software developed by Picarro Inc. The data on air temperature and pressure in the chamber determined by Diver DI 500, Eijkelkamp, were added to the SFP for accurate soil flux calculations. The data logger for air temperature and pressure measurements in the chamber was placed just before the dome was attached. All flux rates for each gas in the study were converted to g or kg per ha per day.

Table 1. Agrochemical characteristics of the soil at study site at the beginning of the measurements, 2018.

Plot	pH_{KCl}	OM, %	P_2O_5 (mg kg^{-1})	K_2O (mg kg^{-1})	N_{total} (g kg^{-1})	C_{total} (g kg^{-1})	Ca: Mg (cmol(+) kg^{-1})	Ca: K (cmol(+) kg^{-1})	Mg: K (cmol(+) kg^{-1})
Plot 1	6.7	3.7	184	276	1.6	15.1	2.7	15.5	5.7
Plot 2	6.9	2.9	109	215	1.6	11.9	2.1	19.5	9.2
Plot 3	6.8	2.8	132	195	1.5	11.5	2.6	21.1	8.0
Plot 4	6.6	3.0	144	263	1.4	12.4	2.7	15.2	5.7
Plot 5	6.7	3.4	151	226	1.6	13.9	2.4	18.1	7.4
Plot 6	6.9	2.8	135	204	1.2	10.6	2.4	21.7	9.0
Plot 7	6.5	3.7	110	276	1.4	10.6	2.8	14.9	5.3
Plot 8	6.1	3.4	107	266	1.3	14.2	3.0	14.6	4.9

Table 2. The scheme of crops and soil tillage in the experimental field. The measurements were carried out in the plots marked in bold. Abbreviations: WW, winter wheat (Triticum aestivum); WR, winter rapeseed (Brassica napus); SB, spring barley (Hordeum vulgare); FB, field beans (Vicia faba); CT, conventional tillage; RT, reduced tillage.

Year	Plot 1 RT	Plot 2 CT	Plot 3 CT	Plot 4 RT	Plot 5 RT	Plot 6 CT	Plot 7 CT	Plot 8 RT
2018	**WW**	**WW**	**WR**	**WR**	**FB**	**FB**	SB	SB
2019	**WW**	**WW**	**SB**	**SB**	WW	WW	**FB**	**FB**
2020	**WR**	**WR**	**FB**	**FB**	WR	WR	**WW**	**WW**
2021	WW	WW	**WW**	**WW**	**SB**	**SB**	**WR**	**WR**

Soil water content was measured at the time of GHG flux measurements at 10 cm depth using Lutron PMS-714 Soil Moisture Meter, but soil water content was measured without consistency due to technical limitations. Preliminary evaluation of available data on soil water content showed minor deviations, therefore it was not considered as robust enough to include in this study. Overview of soil water content during the measurement periods is provided in Figure S1 of the Supplementary Material.

Statistical analysis

The soil flux rates from the Soil Flux Processor (SFP) software were transformed to grams or kilograms per hectare per day and pooled together into one dataset and analysed accordingly. IMB SPSS Statistics version 22 including visual investigations using box plots was used for the statistical analysis. Distribution of the datasets was determined by the Shapiro–Wilk test. Non-parametric tests were applied based on the results of the dataset distribution. The Mann–Whitney U test ($p < 0.05$) was used to assess the effects of the soil tillage treatments on GHG emissions. The Kruskal–Wallis test ($p < 0.05$) was used to determine whether there are statistically significant differences among two soil tillage treatments, years and crops (Ruxton and Beauchamp 2008). The Dunn's *post hoc* tests ($p < 0.05$) were used for pairwise comparisons. The Kruskal–Wallis test ($p < 0.05$) and the Dunn's *post hoc* tests ($p < 0.05$) were used for comparing the cumulative effect of tillage treatments, crops and years. Overview of statistical analysis is presented in Table 3.

Results and discussion

Effect of tillage on GHG emissions

Reduced tillage showed a smaller scattering amplitude of CO_2 and CH_4 emissions. In turn, the scattering amplitude of conventional tillage indicated the effect of tillage on emission potential of soil which was also confirmed by other studies (Alskaf et al. 2021; Dencső et al. 2020; Šarauskis et al. 2020). Assessing only the effect of tillage on GHG emissions, significantly higher N_2O emission was generated by reduced soil tillage with disc harrowing at a depth below 10 cm ($p = 0.002$). Abdalla et al. (2013) review shows that reduced tillage does not always increase N_2O emission, it also depends on temperature, soil water content and soil properties. The average CO_2 emission for both tillage treatments did not differ significantly ($p = 0.750$), which contradicts

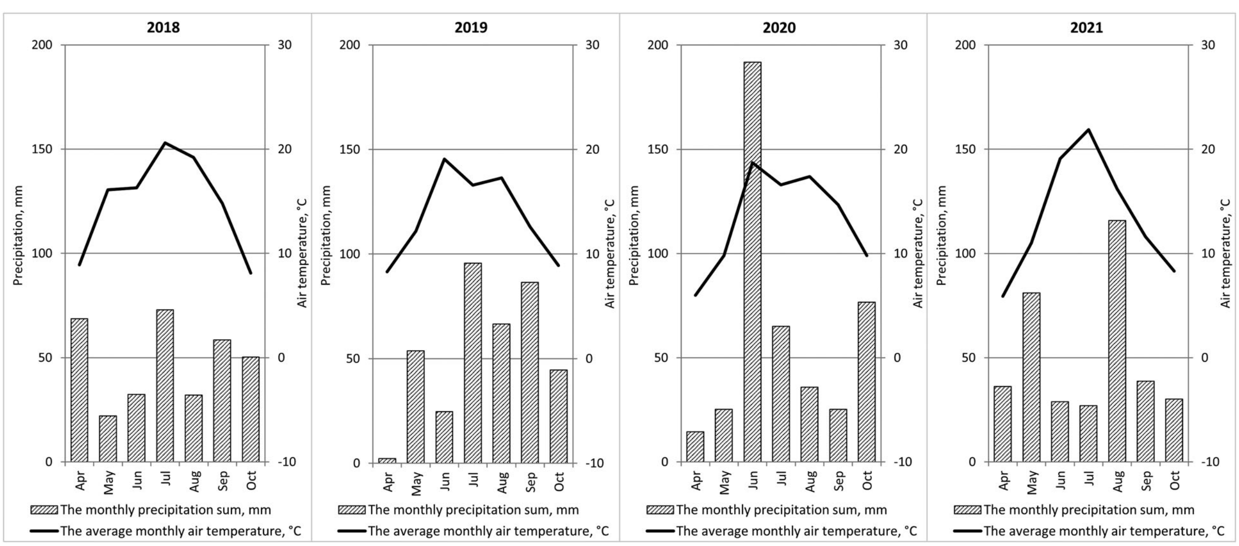

Figure 2. The monthly precipitation amount and average monthly air temperature during the growing seasons of 2018, 2019, 2020 and 2021.

Table 3. Statistical analysis of the data.

Investigation	Analysis
Distribution of the datasets	Shapiro–Wilk test
N_2O emission of tillage treatments	Mann–Whitney U test
CO_2 emission of tillage treatments	Mann–Whitney U test
CH_4 emission of tillage treatments	Mann–Whitney U test
N_2O emission of tillage treatments between years	Kruskal–Wallis test and Dunn's *post hoc* tests
CO_2 emission of tillage treatments between years	Kruskal–Wallis test and Dunn's *post hoc* tests
CH_4 emission of tillage treatments between years	Kruskal–Wallis test and Dunn's *post hoc* tests
N_2O emission of crops	Kruskal–Wallis test and Dunn's *post hoc* tests
CO_2 emission of crops	Kruskal–Wallis test and Dunn's *post hoc* tests
CH_4 emission of crops	Kruskal–Wallis test and Dunn's *post hoc* tests
Cumulative effect of tillage and crop on N_2O between years	Kruskal–Wallis test and Dunn's *post hoc* tests
Cumulative effect of tillage and crop on CO_2 between years	Kruskal–Wallis test and Dunn's *post hoc* tests
Cumulative effect of tillage and crop on CH_4 between years	Kruskal–Wallis test and Dunn's *post hoc* tests

with Alskaf et al. (2021), who have stated that reduced tillage can reduce CO_2 emissions by up to 40%. The results of this study showed that conventional tillage promoted the assimilation of CH_4, which also does not match Alskaf et al. (2021). However, the obtained results showed that there were no significant differences in the formation of CH_4 between tillage treatments ($p = 0.331$) (Figure 3).

GHG emissions from the soil on a yearly basis

The results representing GHG emissions from conventionally tilled plots in the respective years of this study indicated there were significant differences in N_2O emissions between 2018 and 2019 ($p = 0.001$), 2018 and 2020 ($p = 0.005$), 2018 and 2021 ($p = 0.022$), which can be explained by higher average air temperature and lower precipitation during the growing season of 2018, compared to other years (Table 4 and Figure 4). N_2O emissions from reduced tillage plots in 2018 were significantly lower compared to 2019 ($p < 0.001$) and 2020 ($p = 0.048$), but in 2019 N_2O emission was significantly higher than in 2021 ($p = 0.026$). CH_4 emission from both conventional and reduced tillage plots showed significantly higher assimilation of CH_4 in 2018 compared to other years ($p < 0.009$). Also, CH_4 emission from reduced tillage plots in 2019 and 2020 significantly differed ($p = 0.009$). CO_2 emission from the soil in a dry year was lower and showed differences between tillage systems compared to a wet year as CO_2 emission depended on the precipitation during the growing season (Bogužas et al. 2018); but the results of this study did not support these results, which indicated that there were other factors that affected CO_2 emission. There were indicative differences of the direct impact of meteorological conditions on N_2O and CH_4 emissions from clay soil over the years.

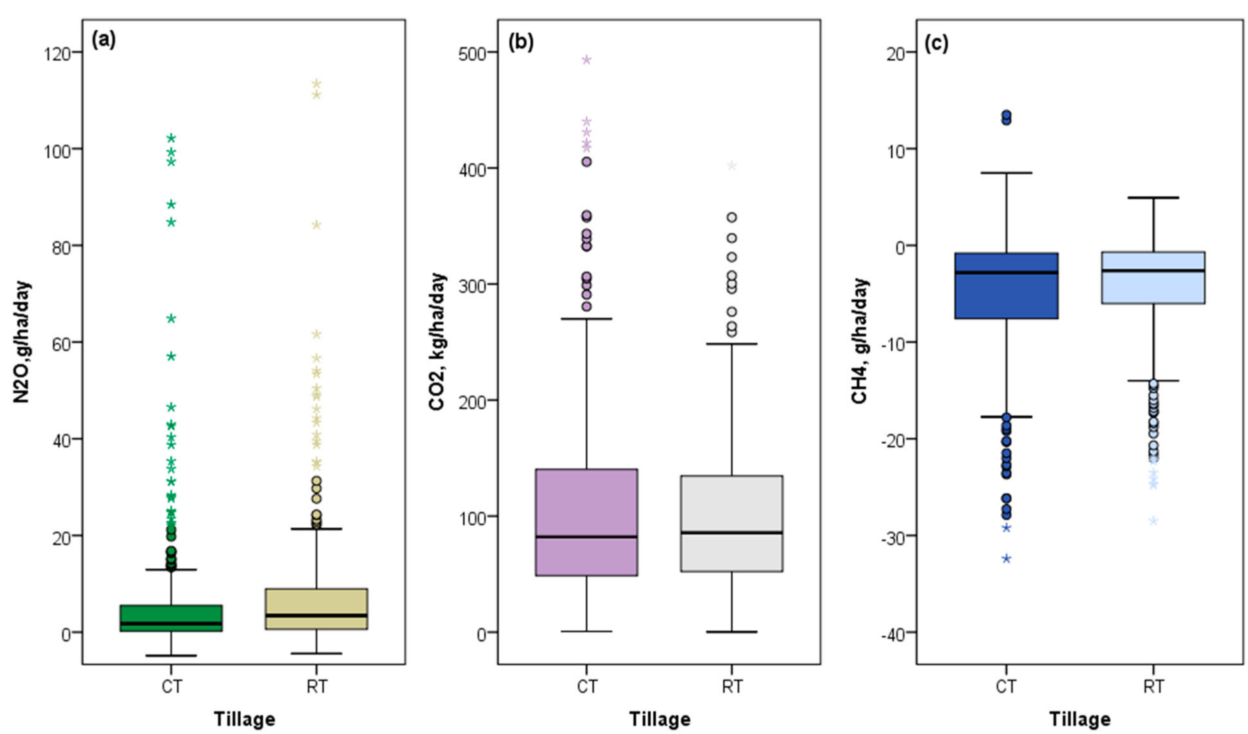

Figure 3. (a) N_2O, (b) CH_4 and (c) CO_2 emissions from *Cambic Calcisol*.

Table 4. Mean value and standard error of the mean (SE) for GHG emission of conventional tillage (CT) and reduced tillage (RT) in study period.

	N_2O (g ha^{-1} d^{-1})				CO_2 (kg ha^{-1} d^{-1})				CH_4 (g ha^{-1} d^{-1})			
	CT		RT		CT		RT		CT		RT	
Year	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
2018	4.0	1.9	3.4	0.8	102.7	8.5	115.3	9.8	−9.2	0.9	−9.5	0.8
2019	9.1	2.2	16.1	3.0	113.0	13.2	106.7	10.4	−5.9	1.0	−5.5	0.8
2020	5.9	1.5	6.3	1.0	103.8	8.9	86.6	5.0	−3.0	0.4	−2.4	0.3
2021	6.5	1.2	6.8	1.3	101.1	8.4	94.6	6.7	−3.8	0.6	−3.2	0.6

Effect of crop on GHG emissions

In order to understand the GHG emissions in the context of agricultural crops, GHG emissions from the following crops – field beans, winter wheat, winter rapeseed and spring barley - were analyzed separately (Table 5).

The highest average N_2O emissions were observed in spring barley plots (10.9 N_2O g ha^{-1} d–^{1}), while the lowest – winter rapeseed (4.6 N_2O g ha^{-1} d–^{1}). Soils where winter rapeseed was grown produced up to 22% higher N_2O emissions than those of winter cereals at the same fertilisation rates (Walter et al. 2015), which was not confirmed by the results of this study. Winter wheat and winter rapeseed emitted statistically significantly ($p = 0.002$ and $p = 0.009$) less N_2O compared to spring barley because of their ability to use fertiliser more efficiently in spring and higher CO_2 because of rising soil organic carbon (Baril et al. 2022). In turn, the study of Shakoor et al. (2021) on the effects of tillage and crops on GHG emissions from soils concluded that barley cultivation significantly increased CO_2 emissions, while the results of this study showed significantly lower CO_2 emission from spring barley compared to winter wheat ($p = 0.003$), and from field bean compared to winter wheat ($p < 0.001$). All crops provided equivalent assimilation of CH_4 ($p = 0.770$).

Cumulative effect of tillage and crop on GHG emissions

In 2018, N_2O emission from RT winter rapeseed was significantly higher compared to RT winter wheat (p <0.001) and CT field bean ($p = 0.01$), but significantly lower compared to CT winter wheat ($p = 0.001$), while in 2019 there was a significant difference in N_2O emissions between RT winter wheat and CT spring barley ($p =$ 0.019). In 2020, N_2O emission from CT winter wheat was significantly lower compared to CT and RT field beans ($p = 0.011$ and $p = 0002$, respectively). There was

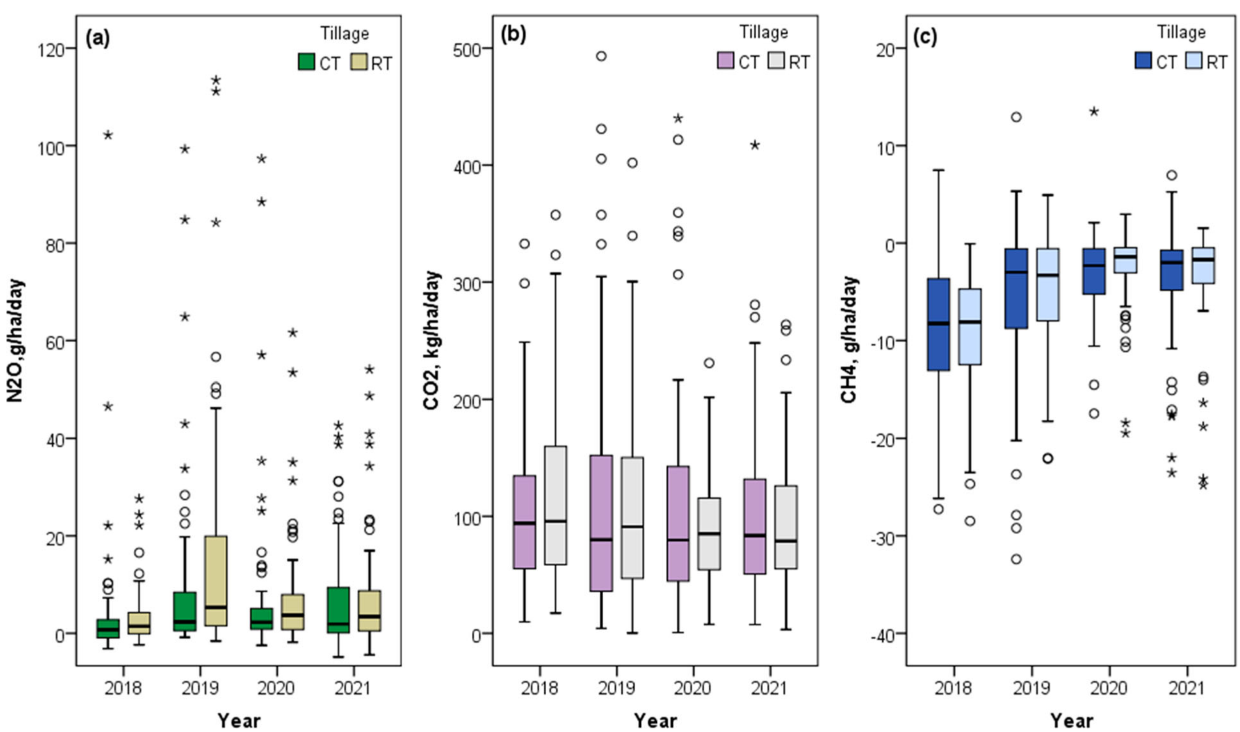

Figure 4. (a) N_2O, (b) CH_4 and (c) CO_2 emissions from *Cambic Calcisol* in 2018, 2019, 2020 and 2021.

Table 5 Mean value and standard error of the mean (SE) for GHG emission of winter wheat (WW), spring barley (SB), field bean (FB) and winter rapeseed (WR) in study period.

	N_2O (g ha-1 d-1)		CO_2 (kg ha-1 d −1)		CH_4 (g ha-1 d −1)	
Crop	Mean	SE	Mean	SE	Mean	SE
WW	7.7	1.2	115.1	5.3	−4.7	0.4
SB	10.9	1.8	87.3	7.3	−4.2	0.5
FB	7.1	1.2	93.1	7.2	−5.2	0.6
WR	4.6	0.7	100.4	5.5	−5.2	0.5

also a significant difference between RT field beans and RT winter wheat ($p = 0.019$). N_2O emission from RT winter wheat was significantly lower compared to RT winter rapeseed ($p = 0.037$), CT and RT spring barley ($p = 0.004$ and $p = 0.001$, respectively), and was significantly lower for CT winter wheat compared to CT and RT spring barley ($p = 0.012$ and $p = 0.004$, respectively) (Figure 5).

The Kruskal–Wallis test grouped by year, tillage treatment and crop as a complex factor showed that there was a significant effect of these factors on N_2O emission from clay soil ($p < 0.001$). The Dunn's *post hoc* test showed significant differences between the 2018 RT winter wheat and the 2021 RT winter rapeseed ($p = 0.042$), the 2020 CT field beans ($p = 0.012$), the 2020 RT winter wheat ($p = 0.007$), the 2019 RT field beans ($p = 0.038$), the 2020 RT field beans ($p = 0.006$), the 2021 CT spring barley ($p = 0.004$), the 2018 RT winter rapeseed ($p = 0.010$), the 2021 RT spring barley ($p = 0.001$), the 2019 RT winter wheat ($p < 0.001$). The 2018 CT winter wheat showed significant differences compared to the 2021 RT spring barley ($p = 0.011$) and the 2019 RT winter wheat ($p < 0.001$). The 2021 RT winter wheat showed significant differences with the 2021 CT spring barley ($p = 0.036$), the 2021 RT spring barley ($p = 0.007$) and the 2019 RT winter wheat ($p < 0.001$). The 2018 CT field beans showed significant differences compared to the 2021 RT spring barley ($p = 0.035$) and the 2019 RT winter wheat ($p = 0.001$).

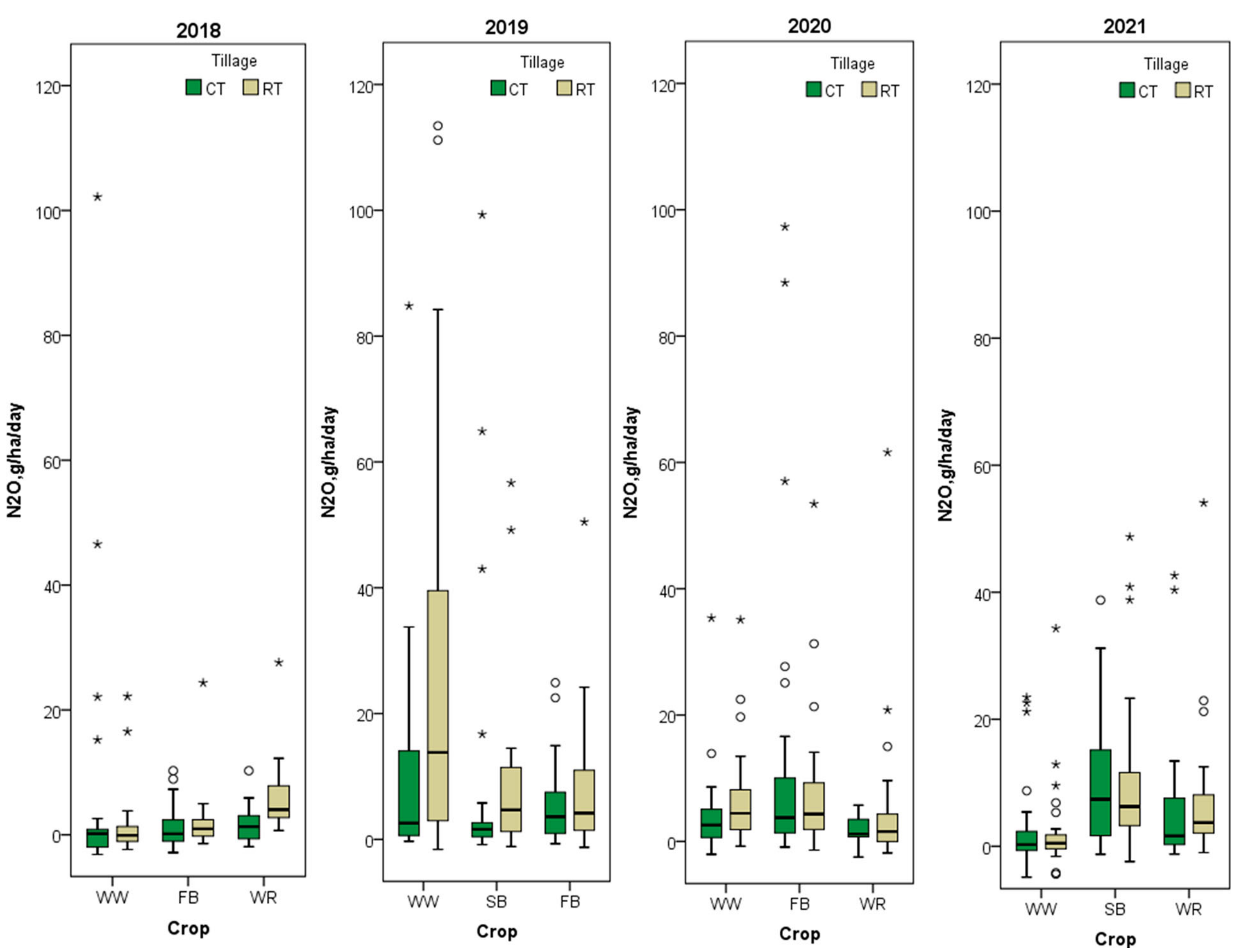

Figure 5. The N_2O emission from the soil under two tillage treatments and four agricultural crops. Abbreviations: WW, winter wheat; WR, winter rapeseed; SB, spring barley; FB, field beans; CT, conventional tillage; RT, reduced tillage. Stars indicate high extreme values (more than 3 interquartile range above quartile 3), and circles indicate high potential outliers (more than 1.5 interquartile range but at most 3 interquartile range below quartile 1).

Statistically significant differences in CO_2 emission are observed only in 2020. CT winter wheat CO_2 emission is significantly higher compared to CT and RT field bean ($p = 0.011$ and $p = 0.002$, respectively), but RT winter wheat CO_2 emission is significantly higher to RT field bean ($p = 0.019$) (Figure 6).

The Kruskal–Wallis test grouped by year, tillage treatment and crop as a complex factor showed that there was a significant effect of these factors on CO_2 emission from clay soil ($p = 0.004$). The Dunn's *post hoc* test showed significant differences between the 2020 RT field beans and the 2020 CT winter wheat ($p = 0.03$).

Comparing mean values of CH_4 assimilation, CT winter rapeseed has a higher CH_4 assimilation, and it is significantly higher compared to RT field beans, RT winter wheat and CT field beans ($p = 0.004$, $p = 0.002$ and $p < 0.001$, respectively). CH_4 assimilation of CT field beans is significantly lower compared to CT winter wheat and RT winter rapeseed ($p = 0.005$) (Figure 7).

The Kruskal–Wallis test grouped by year, tillage treatment and crop as a complex factor showed that there was a significant effect of these factors on CH_4 emission from clay soil ($p < 0.001$). The Dunn's *post hoc* test showed significant differences between the 2018 CT winter wheat and the 2020 RT winter rapeseed ($p = 0.01$), the 2020 CT winter wheat ($p = 0.01$), the 2019 CT winter wheat ($p = 0.012$), the 2019 CT spring barley ($p = 0.023$), the 2021 RT spring barley ($p = 0.013$), the 2021 CT winter wheat ($p = 0.007$), the 2021 RT winter wheat ($p < 0.001$), the 2019 RT winter wheat ($p < 0.001$), the 2021 CT winter rapeseed ($p < 0.001$), the 2021 RT winter rapeseed ($p < 0.001$), the 2020 RT winter wheat ($p < 0.001$), the 2020 RT field beans ($p < 0.001$), the 2020 CT field beans ($p < 0.001$).

Conventional and reduced tillage show different formation of GHG emissions for different crops.

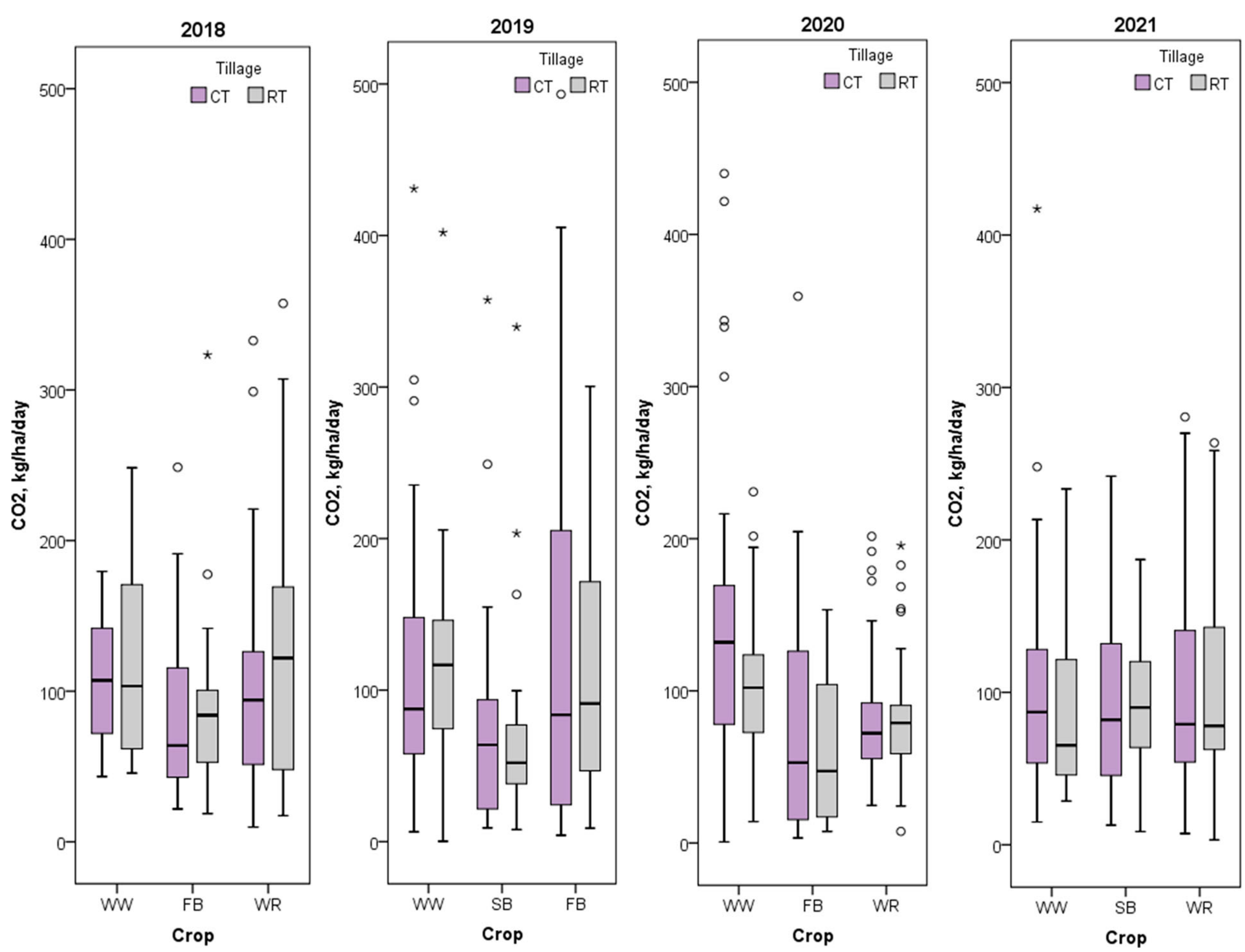

Figure 6. The CO_2 emission from the soil under two tillage treatments and four agricultural crops. Abbreviations: WW, winter wheat; WR, winter rapeseed; SB, spring barley; FB, field beans; CT, conventional tillage; RT, reduced tillage. Stars indicate high extreme values (more than 3 interquartile range above quartile 3), and circles indicate high potential outliers (more than 1.5 interquartile range but at most 3 interquartile range below quartile 1).

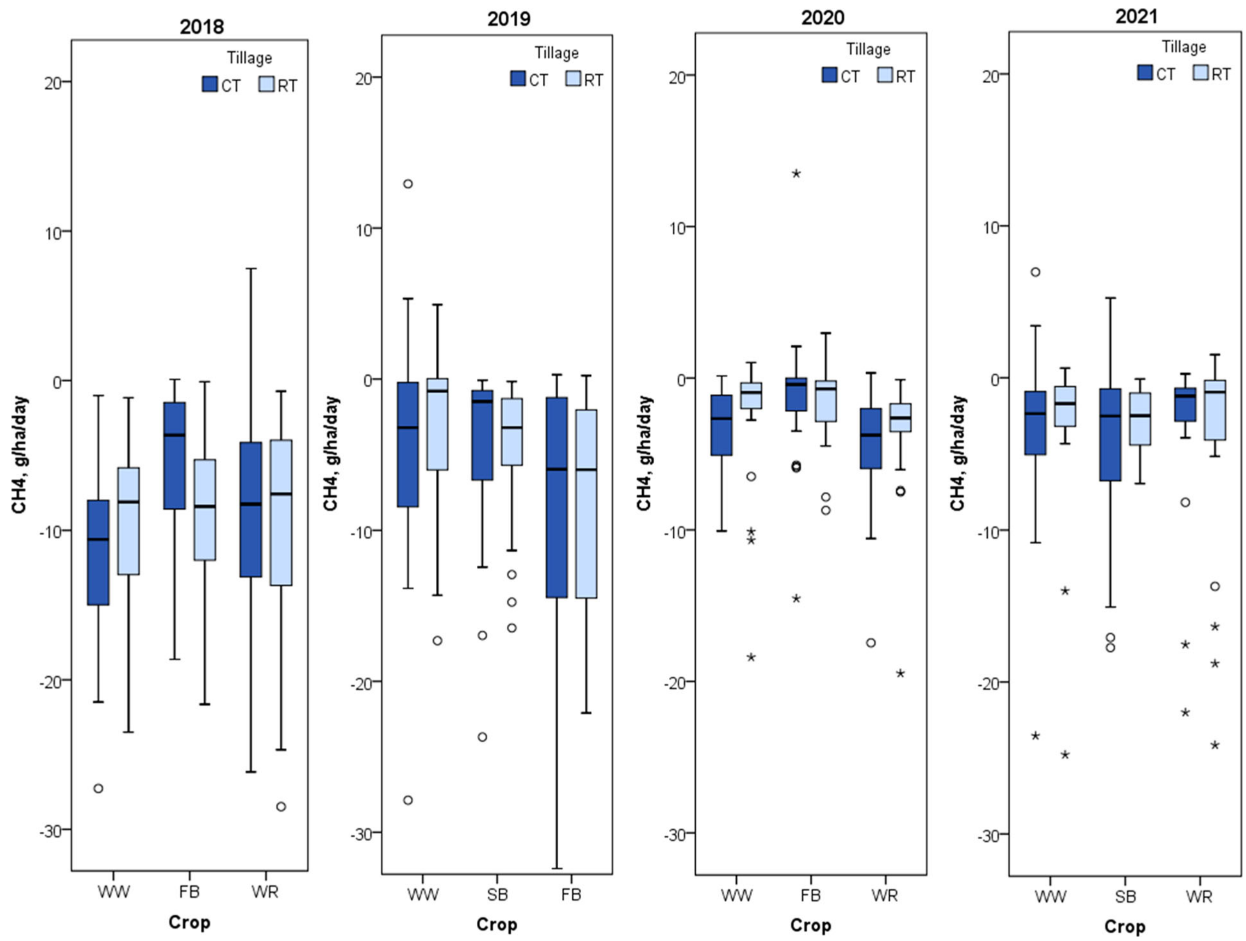

Figure 7. The CH_4 emission from the soil under two tillage treatments and four agricultural crops. Abbreviations: WW, winter wheat; WR, winter rapeseed; SB, spring barley; FB, field beans; CT, conventional tillage; RT, reduced tillage. Stars indicate high extreme values (more than 3 interquartile range above quartile 3), and circles indicate high potential outliers (more than 1.5 interquartile range but at most 3 interquartile range below quartile 1).

During the growing season with warmer and drier meteorological conditions, conventionally tilled winter wheat may produce lower N_2O emission and higher CH_4 assimilation compared to winter wheat and spring barley with reduced tillage treatment in cooler and wetter meteorological conditions. The CH_4 assimilation of winter wheat and winter rapeseed in warmer and drier growing season could be used as a compensatory mechanism for N_2O emissions and therefore be more effective in reducing GHG emissions. Additional positive effect of winter rapeseed in crop rotation is the improvement of soil health by reducing pathogens in the soil and reducing the use of pesticides (Vinzent et al. 2017). Lemken et al. (2017) emphasises that one of the major benefits of legume cultivation is lower GHG emissions compared to other crops, however, winter crops reduce N_2O emissions by increasing nitrogen uptake and reducing the available nitrogen content in soil (Muhammad et al. 2019).

Practical implications and future research

GHG emissions from soil are affected by many on-site variables such as soil water content, soil temperature, nutrient management, land use (Oertel et al. 2016), while the intention of this study was to provide overall assessment in the GHG emissions from clay soil in order to continue investigations on detailed factors affecting GHG emissions. This study emphasised the changes of soil N_2O, CO_2 and CH_4 emissions in response to two soil tillage treatments and four agricultural crops. Although the results do not highlight any specific combination of tillage treatment and crop as potential mitigation measures to reduce GHG emissions, we believe this still is an improvement in understanding that not only farmers' agronomic decisions, but also unpredictable changes in meteorological conditions affect the fluctuation of N_2O, CO_2 and CH_4 emissions from agricultural soils in temperate climatic conditions. For the agricultural sector to move towards GHG neutrality, it is necessary to understand which farm management practices will work best in local conditions to achieve the national socio-economic and environmental objectives. Therefore, one of the activities is also to understand the effects of atypical and extreme weather variability on GHG emissions from agricultural soils. It should be noted that only one aspect that may influence the choice of a particular management practice was included in the study. In this regard, further studies in a temperate climate setting covering most common soil types, crop types and different soil tillage treatments together with economic benefits of the adoption of tillage treatment are would be necessary to validate the results of this study and expand the insights gained. Furthermore, evidence-based research with in-depth understanding of the effects of soil tillage and different crops on GHG emissions from the soils is necessary to incentivise land owners and managers to adopt management practices that reduce GHG emissions from the soils.

Conclusions

The results of this study show that reduced tillage may lead to higher N_2O emissions, while the effects on CO_2 emission and CH_4 assimilation are not statistically significant. Comparing different crops we found that spring barley emits higher N_2O emission than winter wheat and winter rapeseed. Differences in meteorological conditions between years in a temperate climate affect the variability and magnitude of GHG emissions. During the growing season with warmer and drier meteorological conditions, conventionally tilled winter wheat may produce lower N_2O emission and higher CH_4 assimilation compared to winter wheat and spring barley with reduced tillage treatment in cooler and wetter meteorological conditions. Further studies are essential for understanding the on-site variables, long-term effects of meteorological conditions, soil tillage and crops on formation of GHG emissions to incentivise policy makers to promote implementation of management practices that minimise the negative impacts of land management on climate.

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