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ORIGINAL PAPER

Short-term effect of tillage intensity on N_2O and CO_2 emissions

Pascal Boeckx · Katja Van Nieuland ·
Oswald Van Cleemput

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Abstract The effect of tillage on the overall greenhouse gas balance of croplands is not clear. It has been suggested that ceasing tillage increases C sequestration, but has the risk of enhancing N_2O emission, which could switch the greenhouse gas balance from negative to positive. We studied the short-term effect of tillage intensity on N_2O and CO_2 emissions. We changed reduced tillage to conventional tillage or no tillage and performed two tillage operations in two growing seasons. All other parameters such as agricultural management, climate, and crop type at the study site, an intermediately aerated Luvisol in Belgium, were similar. Nitrous oxide and CO_2 emissions were measured event-directed about 40 times per year from September 2006 until December 2008 using a closed chamber technique. We did not observe any significant short-term effect of tillage intensity on N_2O emissions during the 2 years following tillage conversion. The 2-year aggregated N_2O emission was not affected by the absence of tillage, 5.6 kg N_2O–N ha^{-1}, compared to conventional tillage, 4.6±0.9 kg N_2O–N ha^{-1}, or reduced tillage, 4.7±0.3 kg N_2O–N ha^{-1}. Enhanced N_2O emission events in the absence of tillage, 1 year after conversion, could be explained by the combination of higher N application and wetter conditions. Conversion to conventional tillage caused a small, but significant, increase in CO_2 emission over the same period. We conclude that in the short term, none of the tillage intensities had an effect on N_2O emission, and the effect on CO_2 emission was slightly positive when tillage intensity increased. A low short-term risk of increased N_2O emission in the absence of tillage in well-aerated croplands is beneficial agro-environmentally, but the long-term effect should also be assessed via follow-up studies.

Keywords Tillage · Nitrous oxide · Emission · WFPS · Luvisol

1 Introduction

The presence of nitrous oxide (N_2O) in the atmosphere is of global concern due to its high potential contribution to global warming (10% of the net anthropogenic radiative forcing, IPCC (2007)) and its detrimental effect on stratospheric ozone. Agricultural activities are largely responsible for anthropogenic N_2O emissions. Davidson (2009), using a regression model, estimated that globally, 2.0% of manure N and 2.5% of fertilizer N were converted to N_2O between 1860 and 2005. Velthof et al. (2009) calculated that in Europe, between 0.03% and 3.0% of the applied fertilizer N is lost as N_2O and N_2O emissions have been estimated at 2.7 and 2.0 kg N_2O–N ha^{-1} year^{-1} for EU15 and EU27, respectively. Ciais et al. (2010) estimated that N_2O emission from EU25 croplands amounts to 2.8–3.0 kg N_2O–N ha^{-1} year^{-1} (EU15, EU25, and EU27 are the 15th, 25th, and 27th member states of the European Union after the 1995, 2004, and 2007 enlargements, respectively).

In agricultural soils, N_2O is produced via nitrification, denitrification, co-denitrification (Müller et al. 2006), or nitrifier-denitrification (Wrage et al. 2001) by bacteria and fungi (Laughlin and Stevens 2002). In general, N_2O production is controlled by climate, soil type, and land management (e.g., land use, tillage, fertilization, etc.).

P. Boeckx (✉) · K. Van Nieuland · O. Van Cleemput
Laboratory of Applied Physical Chemistry–ISOFYS,
Faculty of Bioscience Engineering, Ghent University,
Coupure 653,
9000 Ghent, Belgium
e-mail: pascal.boeckx@ugent.be

Frequently, it has been proposed that no-tillage farming (NT, negligible soil disturbance, a narrow slot is opened for seed insertion) or reduced tillage farming (RT, not using a moldboard plow for preparing farmland) can be used to mitigate greenhouse gas emissions by increasing soil C stocks (e.g., West and Post 2002) and reducing CO_2 emissions. However, the net global warming impact should be considered with respect to all greenhouse gases, especially N_2O because of its high global warming potential. The effect of tillage on N_2O emissions is variable. Six et al. (2004) found that the net effect of NT on N_2O emission depends on climatic conditions (humid vs. dry) and on the time since conversion to NT. The overall conclusion by Six et al. (2004) was that, with the cessation of tillage, N_2O emissions increased, but that this effect reduced with time after conversion and could even become negative after 20 years. This trend was clearer in humid than in dry climates. Wagner-Riddle et al. (2007) concluded that in the short term (5 years), N_2O emission from NT farming could be lower than with conventional tillage (CT, intensive soil disturbance via moldboard plow and harrowing), but only when NT is combined with a strategy that matches N application rate and timing to crop needs. Rochette (2008) showed that NT increases N_2O emission in poorly aerated soils and has no effect in well-aerated or intermediately aerated soils. Therefore, the largest increase in N_2O emission upon conversion to NT is probably short term (<5 years after conversion) and occurs from poorly drained soils in humid climates, especially when N application does not match crop needs.

In our study, all variables such as soil type, agricultural management, climate, and crop type were similar for the CT, RT, and NT treatments. Our hypothesis was that increasing tillage intensity increases CO_2 emissions while decreasing tillage intensity enhances N_2O emissions. We tested this hypothesis for the conversion of RT to CT (increased tillage intensity) and RT to NT (reduced tillage intensity) in an intermediately aerated Luvisol.

2 Materials and methods

2.1 Experimental site, design, and agricultural management

The study was conducted on a farmer's field in Maulde (Belgium; 50°37′ N, 3°34′ E) from September 2006 to December 2008. The soil contains 17.6% sand, 16.1% clay, and 66.3% silt (Table 2) and is classified as a Luvisol (WRB, http://www.fao.org/AG/agL/agll/wrb/soilres.stm, consulted February 2010). The field site has been under arable management for more than 100 years and was converted from CT to RT in 1995. On 13 September 2006, one third of the field was restored to CT (moldboard plowing to a depth of 30 cm and harrowing the top 10 cm), another third of the field was converted to NT using direct seeding, and the final third continued to be managed by RT (harrowing the top 10 cm). Thus, RT served as the control. At the time of tillage conversion, the soil pH (pH-H_2O) was 6.8, the total organic carbon 1.23±0.08%, the total nitrogen 0.14±0.02%, and the bulk density 1.22±0.06 $\mathrm{g\,cm^{-3}}$. The timing and type of agricultural management between September 2006 and December 2008 is presented in Table 1. For each treatment, three plots were randomly selected for soil sampling and gas flux measurements.

2.2 Environmental parameters

Records of daily precipitation and air temperature were averaged using data from the weather stations at *Anvaing*, *Vezon*, *Tournai*, *Herinnes*, and *Peronnes-Lez-Antoing* located 9.5, 8.5, 13, 22, and 11 km away from the experimental site, respectively. Soil moisture and temperature were determined every 12 h with an e+ SOIL MCT probe (Eijkelkamp, the Netherlands) located 5 cm below the soil surface. The probes were placed in the middle of each plot. From the moisture measurements, water-filled pore space (WFPS, $\mathrm{cm^3\,cm^{-3}}$) was calculated using the formula (Eq. 1):

$$WFPS = \frac{\mathrm{MC} \times \mathrm{BD}}{\mathrm{TPV}} \times 100 \tag{1}$$

where MC is gravimetric moisture content ($\mathrm{cm^3\,g^{-1}}$), BD is bulk density ($\mathrm{g\,cm^{-3}}$), and TPV is total pore volume (1 − BD/soil particle density; soil particle density=2.65 $\mathrm{g\,cm^{-3}}$).

Aggregate size distribution was determined by passing the soil through a graded set of sieves with mesh sizes of 4.8, 2.8, 2, 1, 0.5, and 0.3 mm (De Leenheer and De Boodt 1967). Each aggregate size class was weighed and the mean weighed diameter (MWD) determined using the formula (Eq. 2):

$$MWD = \frac{\sum_{i=1}^{i=n} m_i.d_i}{\sum_{i=1}^{i=n} m_i} \tag{2}$$

where m_i and d_i are mass and the mean diameter of aggregate fraction i, respectively.

Soil mineral N content (NH_4^+ and NO_3^-) was measured each time N_2O emission was determined. A total of three subsamples (one per plot) were collected from each treatment. Soil samples were extracted with 1 N KCl (soil:1 N KCl=1 g:2 mL) and filtered after 1 h using folded filters (Schleicher & Schuell, Germany) with a pore size of 150 µm. Ammonium and NO_3^- contents in the soil extracts were determined colorimetrically using an autoanalyzer (AA3, Bran+Luebbe, Germany).

Table 1 Overview and timing of field management carried out during the measurement campaign (N application in 2008 was different for RT, NT, and CT due to different green manure yields)

Timing	Field management	Specifications
2006		
13/09	RT: Harrowing NT: Killing cover crop CT: Moldboard plowing and harrowing	
14/10	All treatments: Sowing winter wheat	
2007		
04/04	All treatments: Mineral fertilizer application	15 kg NO_3^-–N ha^{-1}, 15 kg NH_4^+–N ha^{-1}, 30 kg urea–N ha^{-1}
26/04	All treatments: Mineral fertilizer application	15 kg NO_3^-–N ha^{-1}, 15 kg NH_4^+–N ha^{-1}, 30 kg urea–N ha^{-1}
02/08	All treatments: Harvest winter wheat	
21/08	All treatments: “Glyfall” application (Glyphosate)	1.77 kg ha^{-1}
04/09	All treatments: Liquid pig manure addition	30,000 L ha^{-1}: 150 kg N ha^{-1}, 136 kg C ha^{-1}
12/09	All treatments: Sowing green manure	Oats: 58 kg ha^{-1} Mustard: 2 kg ha^{-1} Phacelia: 2 kg ha^{-1}
	Total N applied in 2007	270 kg N ha^{-1}
2008		
19/02	All treatments: killing green manure with “Glyfall” (Glyphosate)	1.125 kg ha^{-1}
	N input via green manure:	
	RT	40.1±0.5 kg N ha^{-1}
	NT	24.7±10.2 kg N ha^{-1}
	CT	46.9±5.4 kg N ha^{-1}
05/05	CT: Extirpation (=to root out)	
08/05	All treatments: Mineral fertilizer NT: Sowing maize	90 kg NH_4NO_3–N ha^{-1}
11/05	RT: Harrowing and sowing maize	
12/05	CT: Moldboard plowing, harrowing and sowing maize	
24/10	All treatments: Harvest maize	
30/10	RT: Extirpation (=rooting out) and harrowing	
16/11	CT: Moldboard plowing and harrowing	
17/11	All treatments: Sowing winter wheat	
	Total N applied in 2008	
	RT	130 kg N ha^{-1}
	NT	115 kg N ha^{-1}
	CT	137 kg N ha^{-1}

RT reduced tillage, *NT* no tillage, *CT* conventional tillage

2.3 Crop yields and residues returned to the field

Winter wheat (2007) and maize (2008) were harvested at physiological maturity to determine grain, straw, and residue (stubble plus root) yield (dry weight biomass) and their C and N contents. Residues were left on the surface (NT) of the field or incorporated (CT and RT). Carbon and N contents were determined using an elemental analyzer (ANCA-SL, SerCon, UK) connected to an isotope radio mass spectrometer (20-20, SerCon).

2.4 Nitrous oxide and carbon dioxide fluxes

Gas flux measurements were replicated twice in each plot using closed chambers (six per treatment, diameter 15 cm, height 11 cm) connected to a photo-acoustic infrared gas analyzer (Multi-Gas Monitor Type 1302, Brüel & Kjær, Denmark) equipped with optical filters for N_2O, CO_2, CH_4, and water vapor analysis and connected to a CBISS Intelligent six-channel sampler (CBISS Ltd., England). Boxes were pushed 5 cm into the soil, left open for about half an hour, and then closed; they were placed between plant rows. Measurement campaigns were event-driven (e.g., they were more frequent after fertilization), and approximately 40 flux measurements per year were carried out. Gas analysis lasted 1.5 h, during which five concentration measurements were recorded automatically from each chamber. Measurements were taken between 0930 and 1400 hours. A correction for gas transfer via the CBISS sampler between boxes was carried out according to De Visscher et al. (2000). We determined whether a linear regression or a nonlinear model should be used for flux calculations using the method described by Hutchinson and Mosier (1981)

Statistical differences between CT, RT, and NT treatments were tested by a one-way ANOVA using a Fisher’s least significant difference post hoc test ($P<0.05$) in SPSS version 15. The difference between N_2O and CO_2 emissions in 2007 and 2008 was analyzed statistically by means of a Student’s *t* test at $P<0.05$.

3 Results and discussion

3.1 Soil properties and crop yields

Soil physicochemical properties, temperature, moisture, mineral N content, and N uptake by crops are important drivers for N_2O formation. Soil characteristics for each tillage treatment are presented in Table 2. Soil pH was significantly lower in the CT plots. Total N content did not change significantly following a change in the tillage regime. It is important to note that bulk density increased

Table 2 Soil properties (0–10 cm) of the experimental sites before tillage conversion ("Before", measured 13 September 2006) and at the end of 2008 for RT, NT, and CT

	Sand (%)	Silt (%)	Clay (%)	pH	Total N (%)	Total C (%)	BD (ton m^3)	MWD (mm)
Before	–	–	–	6.8	0.14±0.02	1.23±0.08	1.22±0.06	–
RT	18.8	65.5	15.7	7.0a±0.1	0.13a±0.01	1.48a±0.10	1.29a±0.05	1.82a±0.19
NT	17.7	66.9	15.4	6.9a±0.1	0.13a±0.01	1.33a±0.06	1.49b±0.01	1.30b±0.17
CT	16.2	66.5	17.3	6.6b±0.1	0.12a±0.01	1.25b±0.10	1.35a±0.07	1.07b±0.18

Data are given as averages ± 1 standard deviation, and the same letters in each column indicate no significant differences

BD average bulk density values for the period 27 October 2006–15 July 2008, *MWD* mean weight diameter of aggregates measured on 19 February 2008

RT reduced tillage, *NT* no tillage, *CT* conventional tillage

($P<0.05$) in NT compared to RT and CT, which has consequences for the WFPS. Total C content in the CT plots was significantly lower ($P<0.05$) than in the RT and NT plots. The MWD of soil aggregates was ranked RT> NT>CT. Thus, soil aggregation was reduced following conversion to CT, so the soil organic carbon was less physically protected; hence, there was reduced C accumulation under the CT regime.

Total monthly precipitation and mean monthly air temperature from January 2006 to December 2008 as well as the 30-year average data (1979–2008) are given in Fig. 1. Total precipitation was 968.2 and 952.9 mm in 2007 and 2008, respectively. The 30-year average for the region in which the experimental site is located was 846.4 mm. The average air temperatures were 11.4°C and 10.8°C in 2007 and 2008, respectively. The 30-year average was 10.3°C. In general, 2007 and 2008 were relatively wet and slightly warmer years compared to the average, with three clear precipitation anomalies. April 2007 was exceptionally dry with <4 mm of rain, July 2007 was exceptionally wet

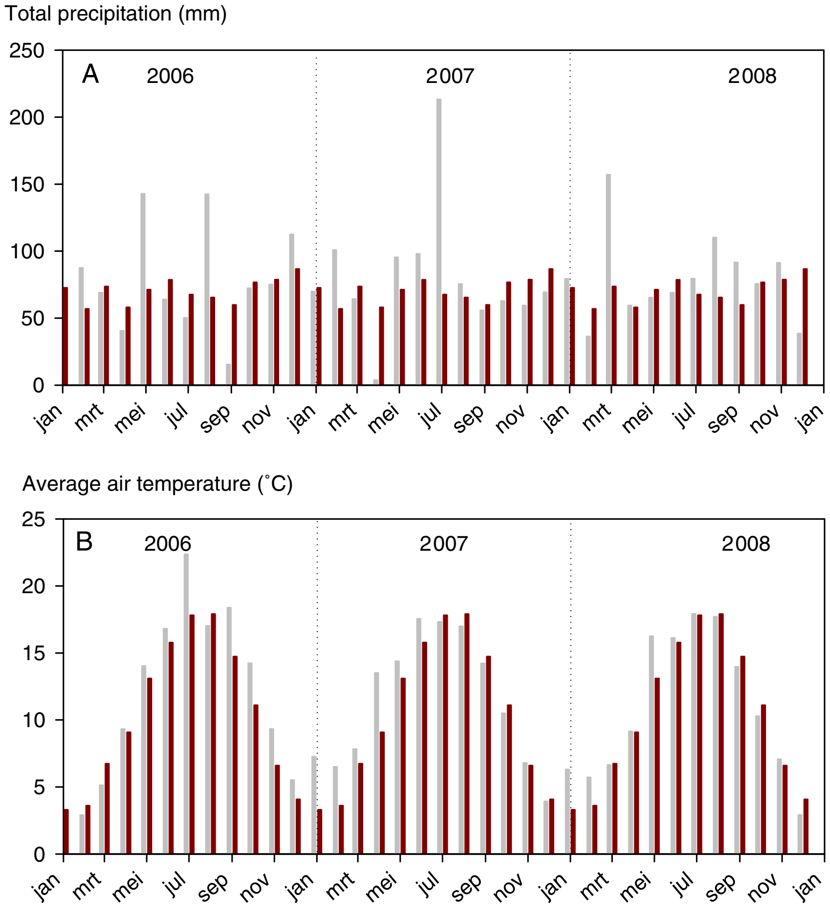

Fig. 1 Cumulative monthly precipitation (**a**) and average monthly temperature (**b**) for 2006, 2007, and 2008 and 30-year averaged data from 1979 to 2008; 30-year-averaged data are given in *black*

with 213 mm, and March 2008 was wet with 157 mm. Furthermore, May to July 2007 and August to September 2008 were wetter than the 30-year average. Both 2007 and 2008 had higher average monthly temperatures in winter and spring and slightly lower temperatures in autumn (September–October).

Soil temperature and moisture are shown in Fig. 2a, b, respectively. In general, soil temperature did not differ between the NT, RT, and CT treatments. Soil temperature was highest between May and September and varied between approximately 15°C and 20°C. From October onwards, soil temperature started to decrease and values between 10°C and 0°C were recorded. In general, the NT plots had a greater WFPS than the RT and CT plots. Due to reduced precipitation, WFPS dropped drastically in all treatments in April 2007 and gradually from June to August 2008.

Soil mineral N content in the 0- to 10-cm layer (Fig. 2c) clearly mirrored fertilizer and manure applications (4 and 26 April and 4 September 2007, and 5 May 2008). In general, after fertilization, NO_3^- content was higher than NH_4^+ content despite the fact that the fertilizer applied also contained NH_4^+. This was probably due to NH_3 volatilization and optimal nitrification because of the neutral soil pH. The mineral N content in the 10- to 30-cm layer followed the same pattern as in the 0- to 10-cm layer (data not shown).

Grain, straw, and residue yields (dry weight) and C and N contents for 2007 and 2008 are shown in Table 3. In 2007, grain and straw yields were significantly ($P<0.05$) higher under the NT regime compared to RT, but not compared to CT. Although not always significant, C and N contents of grain, straw, and residues were ranked as follows: NT>CT>RT. No significant differences were found between tillage treatments in 2008, except with respect to the C content of the maize residues.

Most N was exported (via grain and straw) from the NT area in 2007 and the RT area in 2008. More N was exported in 2008 than in 2007. The amount of C introduced into the soil via crop residues did not differ between the RT, CT, and NT treatments, except for maize residues under the CT regime in 2008.

3.2 Nitrous oxide and carbon dioxide fluxes

The N_2O emissions for 2007 and 2008 are shown in Fig. 2d. The N_2O emission pattern differed between 2007 and 2008. Four emission events can be observed (gray zones in Fig. 2d): April 2007, May 2007, September–October 2007, and May–June 2008. Nitrous oxide emission events generally produced <100 gN_2O–N ha^{-1} day^{-1}. Except for the fertilizer application on 4 April 2007, N_2O emissions were associated with fertilizer application.

The first N_2O emission peak was expected in April 2007 after the first fertilizer application (April 4; Table 1 and Fig. 2d). However, no N_2O emissions were detected from any of the treatment plots. This was because of the extremely dry period in April 2007 (precipitation <4 mm). As a result, WFPS dropped drastically to values below 0.4 cm^3 cm^{-3}. Below this value, no significant N_2O production tends to occur (Bateman and Baggs 2005) even if mineral N is abundant in the soil. There was a second fertilizer application (26 April 2007) shortly before a rainy period in May 2007 (Fig. 1), after which WFPS rose up to approx. 0.8 cm^3 cm^{-3} for the NT area and approx. 0.6 cm^3 cm^{-3} for the RT and CT areas. As a result, the first N_2O emission peak was detected in May 2007. The no-tillage treatment had the lowest N_2O emissions. This could be explained by complete denitrification at favorable WFPS levels of 0.8 cm^3 cm^{-3}. Field operations associated with harvesting winter wheat (2 August 2007) induced a slight emission peak in August 2007. On 4 September 2007, wheat residues were incorporated (CT and RT) and 30,000 Lha^{-1} liquid pig manure was applied. This resulted in increased N_2O emissions during September 2007. This N_2O emission peak was probably due to the nitrification of urea-N followed by denitrification when much higher NO_3^- than NH_4^+ concentrations were present. WFPS was approx. 0.6 cm^3 cm^{-3} for the NT treatment and approx. 0.5 cm^3 cm^{-3} for the other treatments, explaining the higher N_2O emission from the NT than the RT and CT plots during this period. On 19 February 2008, green manure was incorporated (CT and RT), and on 5 May 2008, 90 kg N was applied in the form of NH_4NO_3. As a result, the NO_3^- concentration in the soil drastically increased. Therefore, the N_2O emission peaks in May and June 2008 were probably, again, due to the nitrification of urea-N followed by denitrification when much higher NO_3^- than NH_4^+ concentrations were present. In July 2008, no N_2O emissions were detected, although the NO_3^- concentration remained high and because the nitrification process has ceased. Again, this is explained by a decreasing WFPS under all treatments from mid-June 2008 onwards (Fig. 2b). As a consequence, WFPS became suboptimal for denitrification in the silt loam soil (<0.6 cm^3 cm^{-3}; Bateman and Baggs 2005). Bateman and Baggs (2005) clearly showed that for a silt loam soil (similar to the one at our site), all N_2O was derived from denitrification at 0.7 cm^3 cm^{-3} WFPS, while at 0.35–0.6 cm^3 cm^{-3} WFPS nitrification was the dominant N_2O source.

The total N_2O emissions for 2007, 2008, and 2007 and 2008 together are given in Table 4; they varied between 0.9 and 4.6 kg N_2O–N ha^{-1} $year^{-1}$. This falls within the ranges proposed by Bouwman et al. (2002), Velthof et al. (2009), and Ciais et al. (2010). Total N_2O emissions for all treatments were significantly ($P<0.05$) lower in 2008 than

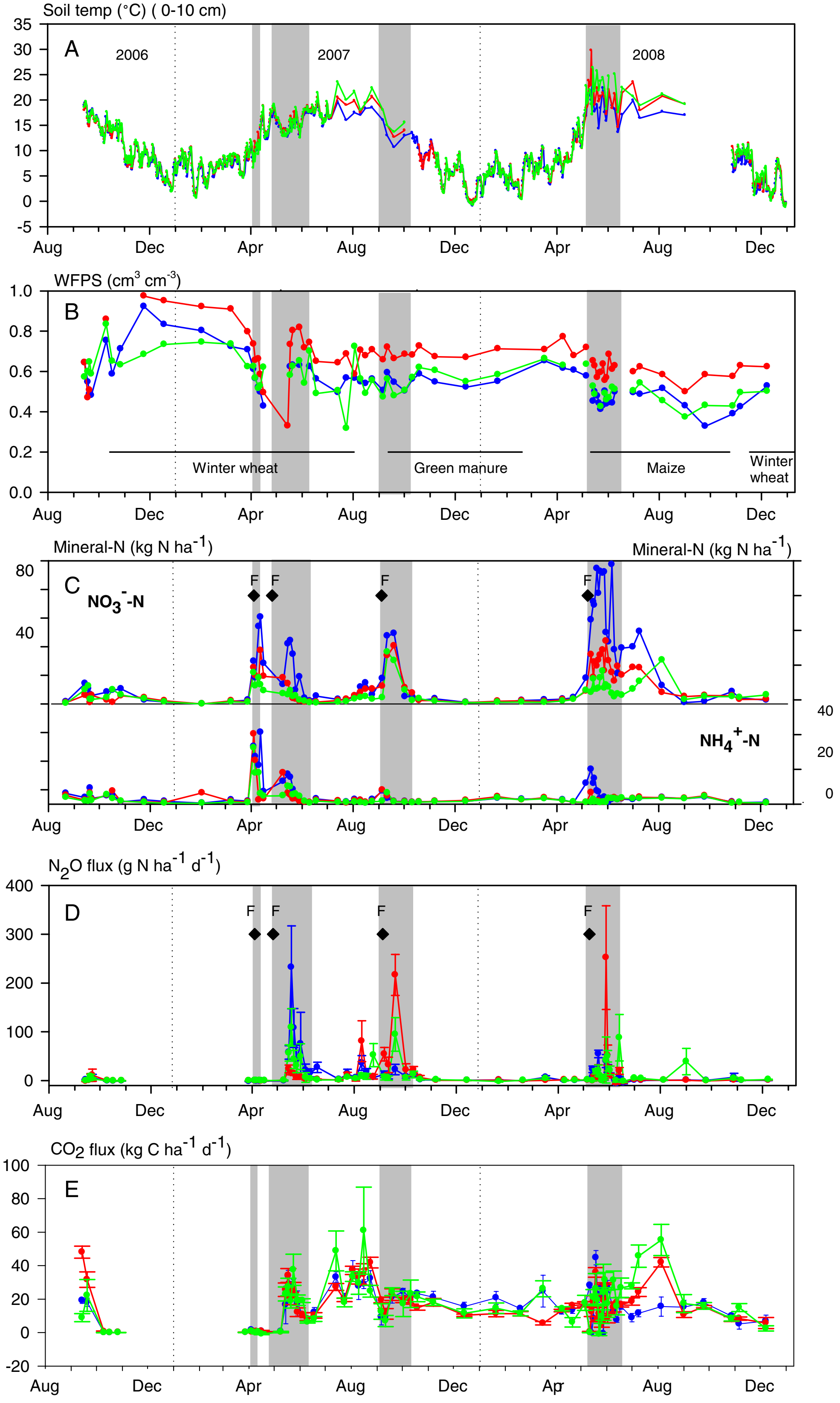

Fig. 2 Soil temperature (0–10 cm) (**a**), water-filled pore space (*WFPS*, 0–10 cm) (**b**), nitrate and ammonium content (0–10 cm) (**c**), N_2O emissions (**d**), and CO_2 emissions (**e**) from September 2006 until December 2008. Data for RT (reduced tillage), NT (no tillage), and CT (conventional tillage) are given in *blue*, *red*, and *green*, respectively. For clarity, no standard deviations are given for nitrate, ammonium, and WFPS. *Gray bars* indicate N_2O emission events after fertilizer (**F**) application. Cumulative precipitations during the first (4 April 2007–15 April 2007), second (26 March 2007–10 June 2007), third (4 September 2007–15 October 2007), and fourth (8 May 2008–20 June 2008) N_2O emission event were, respectively, 0, 116, 81, and 127 mm

Table 3 Winter wheat and maize yield (*dw* dry weight) for RT, NT, and CT

	2007: winter wheat			2008: maize		
	(ton dw ha^{-1})	(kg N ha^{-1})	(ton C ha^{-1})	(ton dw ha^{-1})	(kg N ha^{-1})	(ton C ha^{-1})
RT						
Grain	6.3a±0.8	122.9a±3.6	2.21a±0.06	12.5a±0.1	195.6a±4.3	5.39a±0.11
Straw	5.5a±0.3	51.8a±9.8	2.28a±0.08	10.8a±1.9	96.8a±11.7	4.42a±0.77
Residue	2.7a±0.2	17.2a±2.1	1.03a±0.08	6.1a±1.2	33.7a±12.9	2.09a±0.17
NT						
Grain	8.4b±0.7	191.8b±16.0	3.47b±0.23	13.3a±1.0	167.5a±27.7	5.59a±0.44
Straw	6.7b±0.4	61.9a±13.5	2.80b±0.05	11.8a±0.8	115.6a±14.5	4.91a±0.31
Residue	3.1a±0.3	20.4a±9.0	1.12a±0.13	5.2a±0.1	29.1a±1.1	1.95a±0.10
CT						
Grain	7.7a,b±0.4	169.2c±16.0	2.91c±0.05	11.8a±1.0	182.3a±14.1	5.00a±0.38
Straw	6.6a,b±0.6	65.2a,b±18.1	2.66a,b±0.32	11.2a±0.7	142.8a±8.1	4.64a±0.30
Residue	3.1a±0.3	19.2a±18.1	1.12a±0.09	4.8a±0.7	26.7a±4.5	1.53b±0.19

Data are averages of three 1-m^2 subplots per treatment ± 1 standard deviation. Significant differences between tillage treatments for grain, straw, and residue (part of the crop that remains in the field: stubble plus roots) are indicated with different letters

RT reduced tillage, *NT* no tillage, *CT* conventional tillage

2007. There are a number of possible explanations. First, in 2007, more N was applied to the fields (approx. 140 kg N ha^{-1}, Table 1). Second, in 2008, fertilizer was only applied on one occasion. Third, cumulative precipitations from May to September (the period covering all N_2O emission peaks) were 538 and 416 mm in 2007 and 2008, respectively. This period was clearly wetter (122 mm more rainfall) in 2007, thus favoring N_2O emission. Fourth, in 2008, more N was taken up by the crop than in 2007. Nevertheless, no significant multiple linear regression model using mineral N, WFPS, and temperature (Conen et al. 2000) as variables could be found to predict N_2O emission for the CT, RT, and NT treatments.

Table 4 Annual (n=6 and standard errors) N_2O and CO_2 fluxes for the RT, NT, and CT treatments in 2007, 2008, and 2007+2008

	NT	RT	CT
	(kg N_2O–N ha^{-1})		
2007 (1 year)	4.6a,A (0.7)	3.8a, A (0.4)	3.3a, A (0.5)
2008 (1 year)	1.0a,B (0.2)	0.9a, B (0.2)	1.3a, B (0.7)
2007+2008 (2 years)	5.6a (0.9)	4.7a (0.3)	4.6a (0.9)
	(ton CO_2–C ha^{-1})		
2007 (1 year)	4.6a,A (0.3)	5.0a,A (0.3)	5.0a,A (0.7)
2008 (1 year)	5.0a,A (0.2)	5.1a,A (0.2)	6.7b,B (0.7)
2007+2008 (2 years)	9.6a (0.4)	10.1a (0.6)	11.7b (1.2)

Statistical differences (P<0.05) between 2007 and 2008 and between treatments within a single year are indicated by uppercase and lowercase letters, respectively

RT reduced tillage, *NT* no tillage, *CT* conventional tillage

There were no significant differences in N_2O emissions between the CT, RT, and NT treatments in either 2007 or 2008 (Table 4). However, in 2007, the N_2O emission data exhibited a decreasing trend: NT>RT>CT. In 2008, the trend was CT>NT~RT. For 2007 and 2008 together, N_2O emissions were ranked NT>CT~RT. The N_2O emission ratios NT/RT and CT/RT, respectively reflecting decreased tillage intensity and increased tillage intensity, were calculated. In 2007, NT/RT was 1.21 and CT/RT was 0.86. In 2008, NT/RT was 1.11 and CT/RT was 1.44. Although the differences between tillage treatments were not significant in 2007 and 2008, conversion from RT to NT was associated with a slight increase in N_2O emissions (the NT/RT ratio was 1.1–1.2). In the long term (>30 years NT), Oorts et al. (2007), studying a similar soil type (Luvisol, silt loam), found that NT plots emitted more N_2O and CO_2 than CT plots. CT was associated with slightly lower N_2O emissions (CT/RT=0.9) in 2007 and higher N_2O emissions in 2008 (CT/RT=1.4).

Rochette (2008) examined 25 field studies and grouped them to allow a direct comparison between NT and CT with respect to soil N_2O emission; the classification was based on soil aeration status estimated from drainage class and precipitation during the growing season. According to this approach, our experimental field could be placed in the "medium soil aeration" category (moderate drainage and >400-mm precipitation during the period May–September). Rochette (2008) calculated the no-tillage/tillage N_2O emission ratio from 12 studies with medium soil aeration as 1.13. For the RT to NT conversion, we found an average NT/RT of 1.17, which is close to the average value presented by Rochette (2008). Moreover, the NT/RT was 1.21 in 2007 and 1.11 in 2008 when cumulative precipitations during N_2O emission events were 197 and 127 mm, respectively. The overall higher WFPS in the NT plots (due to its higher BD) may be responsible for the NT/RT values larger than 1. However, Strudley et al. (2008) showed that the response of BD to NT is inconsistent especially in the long term. This suggests that increased WFPS with NT, compared to CT or RT, may also be inconsistent over time.

Carbon dioxide emissions include both heterotrophic and autotrophic respiration. No clear differences in CO_2 emission patterns from the CT, RT, or NT plots were observed (Fig. 2e), except during the period July–August 2008. The total CO_2 emissions for 2007 and 2008 together were 10.1±0.6, 9.6±0.4, and 11.7±1.2 ton CO_2–C ha^{-1} for the RT, NT, and CT treatments, respectively. Conventional tillage was associated with significantly higher CO_2 emissions in 2008, but not in 2007. Over the 2-year period, CT was associated with significantly higher CO_2 emissions than the RT or NT treatments (Table 4). The moldboard plowing technique ensures soil inversion and complete incorporation of all crop residues. Since crop type and the amount of organic residues (except for CT in 2008) were similar for all treatments, it is possible that soil physical properties which enhance soil aeration and reduce protection (lower aggregation; Table 2) of soil organic matter during CT enhance soil organic matter turnover rates (Chatskikh and Olesen 2007), explaining the higher CO_2 emissions under CT in the short term. In combination with lower crop residue input in 2008, this explains why CT was associated with a lower C stock in the top 10 cm than the NT and RT treatments.

4 Conclusions

Over a 2-year period, changing tillage intensity had no effect on N_2O emissions. However, increased tillage intensity enhanced CO_2 emissions. Therefore, the short-term risk of increased N_2O emissions after conversion to NT seems to be low in well-aerated and intermediately aerated soils. However, reconversion to conventional tillage could result in increased C losses. Nitrous oxide emission events and trends could be explained qualitatively on the basis of detailed WFPS, mineral N, soil temperature, and agronomic data. However, we were unable to produce a significant empirical regression model using these soil parameters. We therefore suggest that it may be appropriate to employ data-driven fuzzy models (see Ciais et al. 2010) for predicting site level N_2O emissions, using them to identify the most appropriate combinations of soil physicochemical properties and climate conditions.

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