3-2-2022

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Soil & Tillage Research 220 (2022) 105359

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

No-till farming and greenhouse gas fluxes: Insights from literature and experimental data

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ARTICLE INFO

Keywords:
No-till
Carbon dioxide
Corn-soybean
Nitrous oxide
Plow

ABSTRACT

Tillage intensity may differently impact gaseous losses of C and N to the atmosphere, but data from long-term experiments are relatively few. Yet, this information is needed to better understand C and N losses and gains in agricultural systems. The objective of this study was to determine how tillage intensity affects soil greenhouse gas (GHG) fluxes (CO_2, N_2O, and CH_4) by comparing experimental data from moldboard plow (MP), chisel plow (CP), double disk (DD), and no-till (NT) soils after 38–40 yr of management in a rainfed corn (*Zea mays* L.)-soybean (*Glycine max* (L.) Merr) cropping system. We also reviewed global literature to evaluate the impacts of tillage on soil GHG emissions. After 38–40 yr of management, CO_2 fluxes decreased in this order: MP > CP ≈ DD > NT, indicating that as tillage intensity decreased, CO_2 fluxes decreased. Indeed, daily CO_2 fluxes were typically lower under NT than under MP and CP. Similarly, the overall cumulative CO_2 fluxes across 26-mo of measurement were 1.4–1.8 times lower with NT than MP, CP, and DD soils. Also, MP soils had 1.3 times higher CO_2 fluxes than CP and DD soils. These results are similar to those from our global literature review of 60 studies on CO_2 fluxes. The reduction in CO_2 fluxes in NT was likely due to a combination of increased residue cover, reduced soil temperature ($r = 0.71$; $n = 12$; $p < 0.001$), and increased water content ($r = -0.75$; $n = 12$; $p < 0.001$). Daily N_2O and CH_4 fluxes were highly variable; and cumulative fluxes across the 26-mo study were unaffected by tillage, mirroring findings of our literature review of 37 papers on N_2O fluxes and 24 on CH_4 fluxes. Overall, based on the data from both the long-term experiment and literature review, NT appears to be the best option to reduce losses of CO_2 followed by reduced till (DD), but N_2O and CH_4 fluxes do not generally differ with tillage intensity.

1. Introduction

Greenhouse gases such as CO_2, N_2O, and CH_4 naturally cycle among various terrestrial and atmospheric reservoirs. Soils can be a sink for these gases through photosynthetic capture of C and plant uptake of N followed by conversion of plant material to soil organic matter (SOM). Once the gases are stored as SOM, the soil must be managed in such a way that it retains the organic matter. However, preferred management practices do not always result in the retention of organic matter. Retention of organic matter is a major challenge, as evidenced by the increased emissions of CO_2 (13%), N_2O (81%), and CH_4 (44%) between 2007 and 2016 in the agriculture-forestry sector (IPCC, 2020). The use of soil conservation practices, however, may provide landowners with a strategy to reduce GHG fluxes through management. Because the effectiveness of these practices may change over time, further investigation of soil management effects on soil GHG fluxes is needed.

One key soil management practice commonly used in about 90% of cultivated land area worldwide is tillage (Blanco-Canqui and Ruis, 2018). Despite its usefulness in some applications, conventional tillage can result in negative impacts on SOM through increased losses to erosion and destruction of soil aggregates. The destruction of soil aggregates, which protect organic matter from microbial decay, results in the loss of SOM (Six et al., 2000; Kibet et al., 2016). Conventional tillage also alters microbial activity through changes in substrate availability (i.e. release of organic matter from aggregates), water content, and soil temperature. Many tillage systems incorporate crop residues and

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https://doi.org/10.1016/j.still.2022.105359
Received 30 September 2021; Received in revised form 28 February 2022; Accepted 2 March 2022

exposes bare soil, leading to not only cooler soils in winter and warmer soils in spring, but also generally drier soils compared with NT. These conditions may be more favorable for soil microbial activity, which ultimately drives the biological processes leading to soil GHG fluxes.

Tillage systems vary from high intensity, deep, inversion tillage to NT where the only disturbance may be from fertilizer application or planting (Haddaway et al., 2017). The tillage intensity ranking for some common tillage systems can be: MP>CP>DD>NT. Because of the variability in tillage depth and intensity, tillage systems may differentially affect SOM and soil gas fluxes. For example, Jin et al. (2021) showed greater SOM concentration with lower intensity tillage systems after 30 yr of management. Similarly, Blanco-Canqui et al. (2021) showed SOM did not generally differ by soil depth interval, but did across the 0–60 cm soil profile after 39 yr of management. The researchers showed that MP had 26% lower SOM than NT while CP and DD were intermediate. The large differences in SOM concentration between MP and NT, and the lack of differences between CP and DD compared with NT suggest that significant amounts of soil C can be lost as gases to the atmosphere under the highest intensity tillage system.

Several studies have investigated GHG fluxes under different tillage systems but such systems were mostly short-term (<5 yr) under varying cropping systems including corn (Ussiri and Lal, 2009; Ussiri et al., 2009; La Scala et al., 2006; Prior et al., 2004), corn-soybean rotation (Al-Kaisi and Yin, 2005; Omonode et al., 2007), or a small grain based system (Liu et al., 2018; Kainiemi et al., 2013; Tanveer et al., 2013). Long-term tillage experiments are needed to better understand the impacts of tillage intensity on GHG fluxes. The few available long-term studies on tillage and soil gas fluxes under varying tillage intensities indicate the following:

- CP increased CO_2 fluxes compared with NT after 30–43 yr of tillage under corn-based rotations in Indiana and Ohio, but MP had mixed effects (Omonode et al., 2007; Ussiri and Lal, 2009), which was attributed to differences in temperature and water content among tillage treatments and reduced decomposition due to protection of organic matter.

- Fluxes of CO_2 were similar across MP, CP, and NT after 19 yr in small grain rotation in Spain (Guardia et al., 2016), MP, CP, and NT had similar N_2O fluxes in three studies in corn or small grains after 19–41 yr (Guardia et al., 2016; Tellez-Rio et al., 2017; Omonode and Vyn, 2019), and NT had lower fluxes than at least one tillage system in two corn-based studies after 30–43 yr (Ussiri and Lal, 2009; Omonode et al., 2011).
- MP, CP and NT had similar or reduced N_2O fluxes due to relatively dry conditions and well-aerated soils while wetter soils or those that are poorly aerated soils may show increased N_2O fluxes (Guardia et al., 2016).
- Tillage systems had similar CH_4 fluxes in three of four studies under corn and small grains (Omonode et al., 2007; Guardia et al., 2016; Tellez-Rio et al., 2017) and lower under NT than MP and CP in one (Ussiri et al., 2009).
- Tillage systems had similar CH_4 fluxes are the result of the upland nature of most arable soils, which are typically sinks rather than emitters of $CH_{4.}$

These studies show varying effects of tillage intensity on soil GHG fluxes after long-term use of tillage, suggesting additional data from long-term studies from different climates and soils are needed. Thus, the objective of this study was to determine how tillage intensity affects soil GHG fluxes (CO_2, N_2O, and CH_4) by comparing experimental data from moldboard plow (MP), chisel plow (CP), double disk (DD), and no-till (NT) after 38–40 yr of management in the western US Corn Belt with global literature review.

2. Materials and methods

2.1. Site description and experimental design

We used an ongoing experiment that began in 1981 evaluating six different tillage systems under grain sorghum [*Sorghum bicolor* (L.) Moench]-soybean [*Glycine max* (L.) Merr.] rotation. In 2005, the rotation was changed to corn (*Zea mays* L.)-soybean. The experiment was located at a rainfed site at the University of Nebraska-Lincoln's Rogers Memorial Farm about 10 miles east of Lincoln, NE (40.846° N lat, 96.472° W long). The soil series was an Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls) with ~3% slope. The mean annual temperature was 10 °C and mean annual precipitation was 818 mm. Previous papers from this experiment have evaluated crop yields and compaction during the first decade after establishment (Dickey et al., 1994), soil physical properties and soil C after 33 yr (Kibet et al., 2016), and soil organic C after 39 yr (Blanco-Canqui et al., 2021). The previous studies specifically focused on soil properties that are commonly affected by tillage system but did not consider GHG fluxes, which may also be affected by tillage system or intensity. This long-term, on-going experiment offers a unique opportunity to assess the long-term effects of tillage intensity on GHG fluxes.

The experimental design was a randomized complete block with treatments of MP (to 20 cm depth), CP (to 30 cm depth), DD (to 15 cm depth), DD with cover crop, NT, and NT with cover crop. In the current study, we focused only on treatments of MP, CP, DD, and NT as these tillage systems represent a gradient in tillage intensity (NP>CP>DD>NT). There were three replications. The plot size was 9 m by 23 m with each plot having 12 corn or soybean rows at 76 cm spacing. The MP and CP treatments were imposed in mid-November each year (16 Nov 2017 and 19 Nov 2019) except in November 2018 when wet weather prevented fall plowing. The MP, CP, and DD treatments received disking in early April (12 Apr 2018, 10 Apr 2019, and 9 Apr 2020) and again mid-April (19 Apr 2018, 16 Apr 2019, and 15 Apr 2020) just prior to planting. Plots received 190 kg ha^{-1} as spring knife-applied anhydrous ammonia, plus 47 L ha^{-1} as 10–34–0 in-furrow starter fertilizer at planting in 2019 for corn. No fertilizer was applied to soybean. Planting of corn (80,000 seeds ha^{-1}) and soybean (345,800 seeds ha^{-1}) occurred in late April in 2018–2020. Corn and soybean were harvested in late September to early October. Both phases were present each year, but in separate locations about 1.5 km apart, thus crop rotation was not randomized. We focused on one field, which was in soybean in 2018, corn in 2019, and soybean in 2020. Additional information on the site, experimental design, and management are discussed in Dickey et al. (1994); Kibet et al. (2016); and Blanco-Canqui et al. (2021).

2.2. Measurement of soil gas fluxes

Soil gas fluxes of CO_2, N_2O, and CH_4 were measured for 26 months (April 2018 through June 2020) biweekly to monthly depending on season, weather, and field operations for a total of 24 sampling events. The frequency of measurement is similar to that reported by other tillage system studies measuring soil gas fluxes (Ussiri and Lal, 2009). Fig. 1 and Table 1 report weather data for the sampling period and each sampling date. We determined gas fluxes using a LiCOR 8100 A (LiCOR, Lincoln, NE) automated gas analyzer placed on a 20 cm ring inserted (2.54 cm depth) into the soil on the shoulder of the main crop row. After anhydrous injection, the ring was placed between the anhydrous line and the crop row. The rings were removed after each sampling event to accommodate field operations between measurement times. At the time of measurement, rings were carefully installed to avoid cracking the soil surface within the ring. The soil immediately around the ring (both inside and outside) was gently tapped to ensure a seal. Each ring was allowed to equilibrate for 15 min before measurement, thus all rings were treated equally. We measured gas fluxes at one point per plot for 15 min between 10:00 and 14:00 h, which is similar to other studies

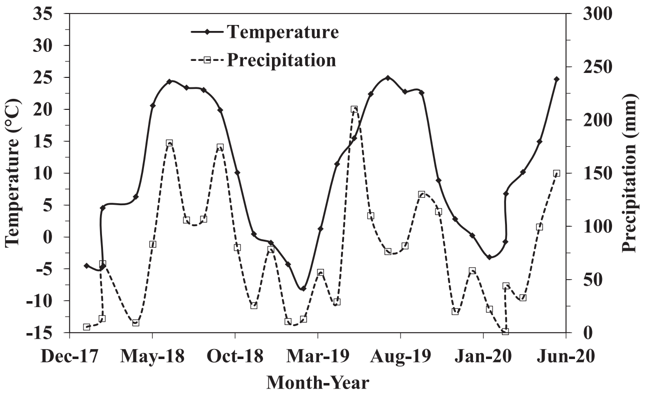

Fig. 1. Mean monthly temperature and total monthly precipitation for years 38–40 yr of a long-term tillage experiment near Lincoln, NE.

reporting GHG fluxes from other systems (Ruis et al., 2018). The soil CO_2 fluxes were determined directly from the IRGA on the LiCOR 8100 A unit. We sampled the LiCOR chamber headspace at 0, 5, 10, and 15 min intervals with syringes through an auxiliary sampling port to determine N_2O and CH_4 fluxes. Sampled gas (25 mL) at each time point was injected into pre-evacuated vials. Vials containing the samples were transported to the lab and stored in the dark at room temperature before analysis. Gas concentrations within each vial was assessed using a Varian 450 gas chromatograph (Varian, Walnut Creek, CA) equipped with separate detectors for the simultaneous measurement of N_2O (electron capture detector), CH_4 (flame ionization detector), and CO_2 (thermal conductivity detector). The CO_2 values reported here are from the LiCOR unit only. The gas concentration data from the gas chromatograph in mg L^{-1} were converted to a per area basis (ng m^{-2} d^{-1}) as described by Parkin and Venterea (2010). Note that we report the fluxes of CO_2-C, N_2O-N, and CH_4-C, which is the amount of C or N associated with the CO_2, N_2O, and CH_4 fluxes.

We determined the cumulative fluxes by season, annually, and across the 26-mo measurement period. Cumulative fluxes were calculated by multiplying the mean flux rate on two consecutive sampling times by the number of days between sampling events as described by Guardia et al. (2016). The seasonal fluxes included three in-season and two off-season. In-season measurements were the main crop growing period from late April to November while off-season measurements were the non-crop period from November to late April. Thus, our in-season cumulative fluxes include: in-season year 38, in-season year 39. Note that fluxes were monitored late April 2020 through June 2020 for a partial monitoring of a third in-season during year 40; however, due to the truncated nature of this season we only consider fluxes from that time in the daily and 26-month cumulative timeperiods. Our off-season fluxes include: off-season year 38 and off-season year 39. Annual cumulative fluxes correspond to year 38 (2018–2019) and year 39 (2019–2020) where fluxes were the sum of all fluxes from late April 2018 through mid-April 2019 and from late April 2019 through mid-April 2020, respectively. Total cumulative fluxes were the result of summing all fluxes for the 26-mo period.

2.3. Determination of soil properties associated with greenhouse gas fluxes

Soil gas fluxes can be driven by soil microbial and root activities, which are driven by soil properties of temperature, water content, and air-filled porosity. Further, soil organic C, total N, and particulate organic matter concentrations may drive microbial activity as they serve as microbial food sources. Thus, we examined the impacts of tillage intensity on these soil properties and their relationships with soil gas fluxes. To assess tillage-induced changes to soil temperature, water content, and air-filled porosity, we measured these properties at each of the 24 measurement dates. Soil temperature was determined using a digital thermometer (Spot On, DT3-S, Turf-Tec International, Tallahassee, FL) to a soil depth of 5 cm at 10 sampling points on the shoulder of main crop rows within each plot. We also collected two 5 cm × 5 cm soil cores per plot near the chamber base to assess volumetric water content and air-filled porosity. Note that the 24 sampling events did not alter the microsite near the chamber due to tillage and subsequent relocation. Soil cores were collected during each gas sampling event and placed in plastic bags to preserve water content. Soil cores were weighed, dried at 105 °C for 24 h, and reweighed to determine water content. Gravimetric water content from the oven-dry soil cores was converted to volumetric water content using bulk density determined by the core method (Blake and Hartge, 1986). Air-filled porosity was determined by calculating total porosity assuming a particle density of 2.65 g cm^{-3} and then calculating the difference between total porosity

Table 1
Weather data and conditions at each soil gas sampling date during 2018, 2019, and 2020 after 38, 39, and 40 yr, respectively of a tillage experiment near Lincoln, NE.

Year	Date	Maximum Temperature	Minimum Temperature	24-hr Precipitation	Conditions
		(°C)	(°C)	(mm)	
Year 38	24 April 2018	22.8	0.56	0.76	Overcast
	4 May 2018	26.7	8.33	1.02	Mostly sunny
	18 May 2018	26.7	13.9	0	Overcast
	30 May 2018	26.4	16.1	29.5	Sunny
	13 June 2018	26.7	13.9	0.25	Overcast
	29 June 2018	35.0	26.7	0	Sunny
	9 July 2018	32.8	18.9	0	Sunny
	24 July 2018	28.9	12.8	0	Sunny
	3 August 2018	33.3	21.1	8.89	Sunny
	18 September 2018	34.4	19.4	11.4	Sunny
	6 November 2018	9.44	-4.44	7.11	Sunny
	22 March 2019	17.2	-3.89	0	Sunny
	2 April 2019	13.9	0.56	2.54	Partly sunny
	13 April 2019	12.8	-1.67	0	Sunny
Year 39	27 April 2019	18.9	0.56	9.14	Mostly cloudy
	10 May 2019	16.7	2.22	0	Sunny
	24 June 2019	25.6	15.6	2.29	Sunny
	13 December 2019	5.56	-8.33	0	Sunny
	25 March 2020	23.3	6.11	0	Mostly cloudy
	7 April 2020	30.56	7.22	0	Cloudy and foggy
Year 40	24 April 2020	16.1	6.11	5.33	Cloudy
	11 May 2020	10.6	0	0	Cloudy
	29 May 2020	26.1	8.33	0	Sunny
	12 June 2020	31.7	14.4	0	Sunny

and volumetric water content. We used data from Kibet et al. (2016) for the same experiment to study relationships of gas fluxes with soil organic C, total N, and particulate organic matter concentrations.

2.4. Literature review approach

To further understand how tillage affects GHG fluxes beyond our experimental data, we reviewed published literature using Web of Science with no set date range. The search terms included: tillage, plow, CO_2, carbon dioxide, N_2O, nitrous oxide, CH_4, methane, and GHG fluxes. We avoided incubation and pot studies as these do not always reflect field conditions. We did not include vegetable crops, orchards, and olive (*Olea europaea* L.) groves as our focus was on row crops for consistency in comparison with the experimental data. We only included studies that compared MP, CP, or DD with NT for consistency in comparison with our experimental data. We avoided studies with cover crops and included those that had a no cover crop control in all tillage systems. We only included papers published in English. In total, we found 62 study comparisons (NT vs tillage) for CO_2, 38 for N_2O, and 24 for CH_4. When data were presented in a figure, we used Web Plot Digitizer to extract the data (Rhogati, 2020). We counted the number of comparisons where MP, CP, and DD increased, decreased, or had no effect on soil gas fluxes compared to NT.

2.5. Statistical analysis

To analyze our field data, we used separate ANOVAs from the PROC GLM procedure due to the different timeframes (daily, in-season, off-season, annual cumulative, and total cumulative). Data for the daily gas fluxes, temperature, water content, and air-filled porosity were analyzed using ANOVA from the PROC GLM procedure in SAS for a randomized complete block design with tillage treatment and measurement date as the fixed effects and replication as the random effect (SAS Institute, 2020). For the seasonal cumulative fluxes, PROC GLM was also used with period (in-season 38 under soybean and in-season 39 under corn and off-season period 2018–2019 or 2019–2020) and tillage treatment as the fixed effects and replication as the random effect. For the cumulative fluxes of the experiment, tillage treatment was the fixed effect for the PROC GLM procedure. When tillage system affected GHG fluxes at $p < 0.05$, separation of treatment means was evaluated through Least Significant Differences. To study changes to soil gas fluxes induced by related soil properties, correlation analysis was performed using PROC CORR.

3. Results

3.1. CO_2 fluxes

Daily CO_2 fluxes were affected by measurement date, tillage system, and their interaction (Table 2). Across all dates, CO_2 fluxes decreased with decreasing tillage intensity: MP>CP≈DD>NT. The average fluxes across all dates were: 5.5 g CO_2-C m^{-2} d^{-1} for MP, 4.1 for CP, 4.7 for DD, and 2.6 for NT. Fig. 2A shows the impact of tillage system and date on CO_2 fluxes throughout the experiment period. Tillage system had no effect on CO_2 fluxes on 15 of 24 measurement dates and affected fluxes to varying degrees on the remaining 9 dates (Fig. 2A). Five of the nine dates showed NT had the lowest CO_2 fluxes, all of which occurred in spring and early summer within one or two months of double disking. The remaining four dates showed mixed effects of tillage on CO_2 fluxes.

Seasonal CO_2 fluxes were affected by tillage system, season, and their interaction (Table 2). During the two in-season measurement periods (in-season year 38 and 39), MP had 2.18–2.59 fold higher CO_2 fluxes than NT. The CO_2 fluxes from CP and DD were intermediate and effects varied annually. During the two off-season measurement periods (off-season year 38 and 39), there were varying effects of tillage. In off-season year 38, there was no effect of tillage on CO_2 fluxes, attributable to the lack of tillage due to wet conditions. However, during off-season year 39, CO_2 fluxes were in this order: MP≈CP≈DD>NT. Across all tillage systems, CO_2 fluxes were generally higher during in-season year 38 and off-season year 38 than the in-season year 39 and off-season year 39.

Table 2
ANOVA *p*-values for CO_2-C, N_2O-N, and CH_4-C gas fluxes on daily, seasonal (in-season during crop growing period and off-season during non-crop growing period), annual cumulative, and total cumulative (across 26-mo study) timeframes for a long-term (38–40 yr) tillage experiment located near Lincoln, NE.

	CO_2-C	N_2O-N	CH_4-C
	Daily Gas Fluxes		
Measurement Date (D)	< 0.001	0.002	0.29
Treatment (T)	< 0.001	0.71	0.75
D×T	< 0.001	0.41	0.11
	Seasonal Gas Fluxes		
In-season or Off-season Period (P)	< 0.001	0.002	0.72
Treatment (T)	< 0.001	0.76	0.27
P × T	0.016	0.64	0.44
	Cumulative Fluxes During Year 38		
Treatment	0.05	0.72	0.41
	Cumulative Fluxes During Year 39		
Treatment	0.01	0.73	0.66
	Total Cumulative Fluxes Across 26-Mo Measurement Period		
	CO_2	N_2O	CH_4
Treatment	0.007	0.93	0.23

Annual cumulative CO_2 fluxes for years 38–40 of the experiment as well as total cumulative CO_2 fluxes for the 26-mo measurement period were affected by tillage system (Table 2). In year 38, MP had 1.83 times higher CO_2 fluxes than NT, but CP and DD were similar to both MP and NT. In year 39, tillage system affected CO_2 fluxes in this order MP > CP ≈ DD ≈ NT. Cumulative fluxes across the 26-mo measurement period showed that MP had 1.79 times higher and CP and DD 1.40 times higher CO_2 fluxes than NT. Moldboard plow had 1.28 times higher CO_2 fluxes than CP and DD (Table 4).

3.2. N_2O and CH_4 fluxes

As shown in Table 2, only measurement date affected daily N_2O fluxes. Fluxes of N_2O were highly variable on a daily basis as indicated in Fig. 2B. Seasonal N_2O fluxes were only affected by season (Table 3). Fluxes of N_2O were higher during the in-season 38 than all other seasons. Annual and 26-mo cumulative N_2O fluxes were unaffected by tillage system (Table 4). Measurement date, tillage, and their interaction did not affect daily CH_4 fluxes (Table 2). Daily CH_4 fluxes were highly variable (Fig. 2C). Seasonal, annual, and 26-mo cumulative CH_4 fluxes were unaffected by tillage system (Tables 3 and 4).

3.3. Factors affecting soil gas fluxes

Fig. 3 summarizes the impacts of tillage system on daily soil temperature, water content, and air-filled porosity. Across all dates, tillage systems did not affect average soil temperature. Tillage systems affected volumetric soil water content in this order: MP (14.3%) ≈ DD (16.2) < NT (19.5) with CP similar to both MP and DD soils. Tillage systems affected soil temperature on 11 of 24 measurement dates. No-till soils were cooler than all other tillage systems on 2 of the 11 dates. They were cooler than MP soils on five dates. The remaining dates showed mixed effects of tillage systems on soil temperature. Tillage systems affected water content on 18 measurement dates. No-till soils were wettest on 12 of those 18 dates. The remaining dates showed mixed effects of tillage systems on soil water content. Across all dates, the average air-filled porosity decreased in this order: MP (48.4%) ≈ CP (48.8%) ≈ DD (46.8%) > NT (41.1%). Air-filled porosity was affected by tillage systems on 12 dates. On 5 of the 12 dates, no-till soils had the lowest air-

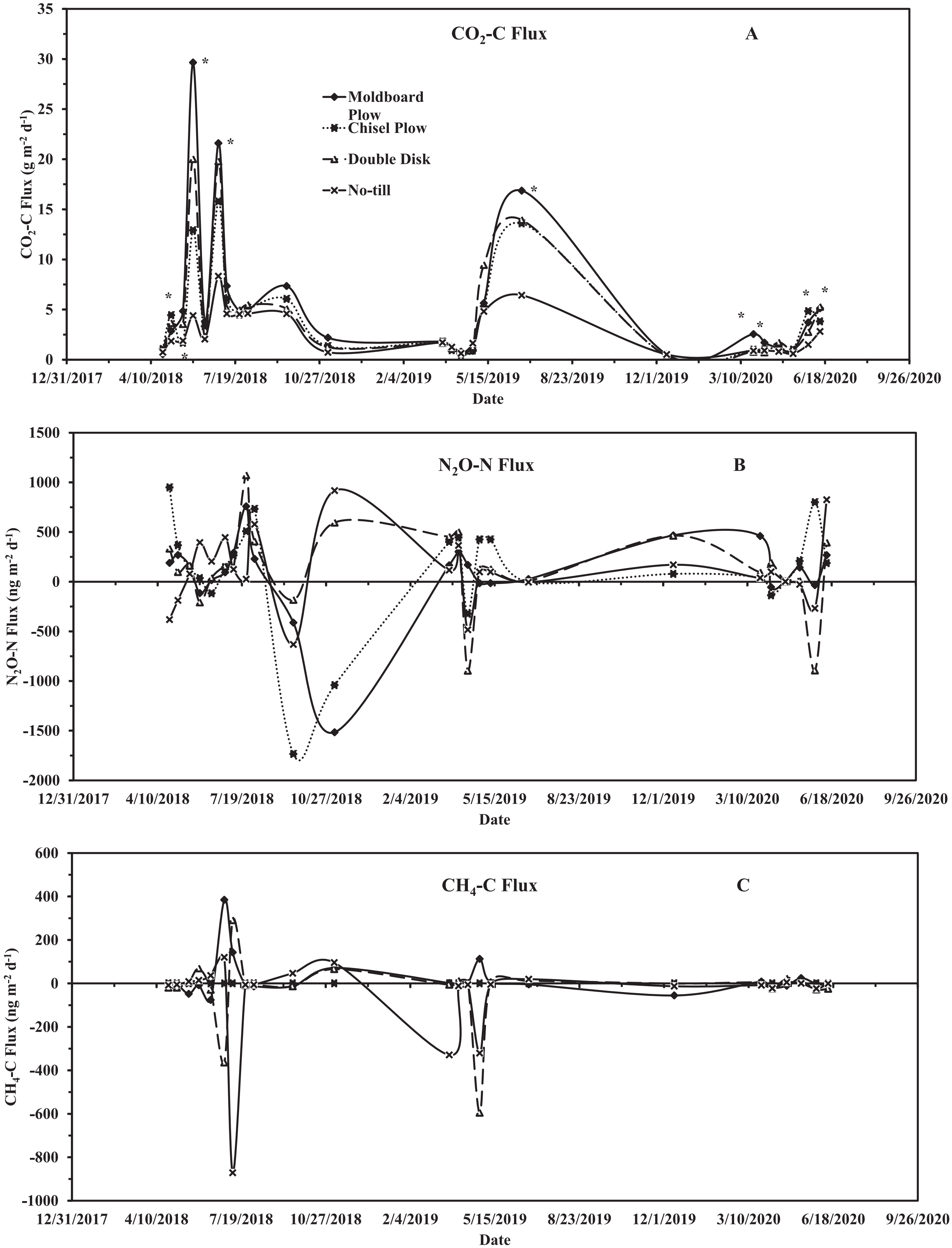

Fig. 2. Impact of 38–40 yrs of moldboard plow, chisel plow, double disk, and no-till on CO_2-C (A), N_2O-N (B), and CH_4-C (C) fluxes at 24 measurement dates between April 2018 and June 2020 from an experiment near Lincoln, NE. *denotes dates when tillage significantly affected fluxes at $p < 0.05$.

Table 3
Impact of long-term (38–40 yr) moldboard plow, chisel plow, double disk, and no-till on CO_2-C, N_2O-N, and CH_4-C fluxes during in-season (crop growing period) or off-season (non-crop growing period) periods from April 2018 through June 2020 for an experiment near Lincoln, NE. Treatments with the same lowercase letter within a column are not significant at $p < 0.05$. Different uppercase letters within a row are significant at $p < 0.05$. No letter denotes non-significant. Values in parentheses are the standard deviation.

Tillage System	In-Season 38	Off-Season 38	In-Season 39	Off-Season 39
	CO_2-C (Mg ha^{-1})			
Moldboard	10.1 (1.9) aA	11.6 (2.9) A	1.8 (0.7) aB	4.6 (1.2) aB
Chisel	6.7 (0.9) bB	10.0 (1.9) A	1.1 (0.6) abC	2.4 (0.3) bC
Double Disk	8.0 (1.0) abA	8.9 (0.5) A	1.1 (0.2) abC	2.0 (0.2) bB
No-Till	3.9 (0.6) cB	8.2 (1.3) A	0.8 (0.1) bC	2.0 (0.2) bB
Mean	7.2 (2.6) b	9.7 (2.1) a	1.2 (0.5) d	2.8 (0.7) c
	N_2O-N (g ha^{-1})			
Moldboard	26.8 (2.8)	-6.8 (34.3)	4.6 (1.6)	3.46 (2.9)
Chisel	19.2 (13.8)	7.3 (2.3)	-1.4 (6.0)	1.4 (7.4)
Double Disk	25.8 (23.7)	0.9 (7.3)	-7.9 (15.5)	-1.5 (16.3)
No-Till	8.1 (22.1)	-1.4 (7.0)	5.4 (6.3)	10.1 (3.3)
Mean	19.9 (13.6) a	0.2 (16.2) b	0.008 (9.5) b	3.36 (9.0) b
	CH_4-C (g ha^{-1})			
Moldboard	1.5 (4.9)	-0.5 (8.7)	0.07 (0.5)	-0.04 (0.8)
Chisel	-1.6 (6.0)	-0.05 (0.2)	-0.02 (0.1)	-0.09 (0.3)
Double Disk	0.8 (3.1)	0.07 (0.5)	-0.4 (0.4)	-0.2 (0.4)
No-Till	-7.2 (11.3)	-3.4 (5.3)	0.07 (0.3)	-0.07 (0.3)
Mean	-1.6 (6.9)	-0.9 (2.8)	-0.08 (0.4)	-0.3 (0.5)

Table 4
Impact of long-term (38–40 yr) moldboard plow, chisel plow, double disk, and no-till on total and annual cumulative CO_2-C, N_2O-N, and CH_4-C fluxes between April 2018 through June 2020 (26 months) from an experiment near Lincoln, NE. Treatments with the same lowercase letter within in-season or off-season periods are not significant at $p < 0.05$. No letter denotes non-significant. Values in parentheses are the standard deviation.

	Tillage System	CO_2-C	N_2O-N	CH_4-C
		Mg ha^{-1}	g ha^{-1}	
Year 38 Annual Cumulative Fluxes During	Moldboard	11.6 (2.9) a	21.3 (1.4)	3.2 (4.2)
	Chisel	10.0 (1.9) ab	24.5 (48.8)	-2.5 (0.5)
	Double Disk	8.9 (0.5) ab	27.0 (12.7)	-0.9 (5.9)
	No-till	8.2 (1.3) b	7.1 (18.1)	-10.0 (16.9)
Year 39 Annual Cumulative Fluxes During	Moldboard	4.6 (1.2) a	-3.8 (35.9)	-0.8 (0.4)
	Chisel	2.4 (0.3) b	6.8 (5.1)	-1.7 (1.6)
	Double Disk	2.0 (0.2) b	-1.5 (10.1)	-0.1 (0.3)
	No-till	2.0 (0.2) b	12.6 (11.2)	-0.05 (0.2)
Total Cumulative Fluxes During 26-Mo Measurement Period	Moldboard	31.3 (5.0) a	1.3 (1.6)	0.01 (0.3)
	Chisel	23.9 (3.2) b	1.4 (6.3)	0.2 (0.4)
	Double Disk	24.8 (1.1) b	1.9 (8.2)	0.4 (1.0)
	No-till	17.5 (1.8) c	1.3 (4.9)	-0.3 (0.03)

filled porosity but had variable effects in the remaining dates.

The correlation analysis showed CO_2 fluxes were positively correlated with temperature and negatively correlated with water content on daily, seasonal, annual, and 26-mo cumulative timeframes except during off-season year 38, in-season year 39, and year 38 (Table 5). Fluxes of CO_2 were positively correlated with air-filled porosity across all timeframes except daily, off-season year 38, in-season year 39, and annual cumulative for both years 38 and 39 (Table 5). Surprisingly, fluxes of CO_2 were negatively correlated with soil organic C in all measurement timeframes except off-season year 39. Fluxes of CO_2 were also negatively correlated with total N in all timeframes and negatively correlated with particulate organic matter except in some cases. Note that soil organic C, total N, and particulate organic matter concentrations were measured for the 0–10 cm depth.

Across all dates, N_2O was negatively correlated with temperature and positively correlated with water content (Table 5). However, seasonal, annual, and 26-mo cumulative fluxes of N_2O were generally not correlated with temperature, water content, air-filled porosity, nor with concentrations of soil organic C, total N, and particulate organic matter. Daily fluxes of CH_4 were negatively correlated with temperature and positively correlated with water content (Table 5). Seasonal and annual CH_4 fluxes were generally not correlated with temperature, water content, air-filled porosity, nor with concentrations of soil organic C, total N, and particulate organic matter concentrations. Cumulative CH_4 fluxes were positively correlated with temperature and air-filled porosity and negatively correlated with water content and particulate organic matter concentration.

4. Discussion

4.1. CO_2 fluxes

Results from years 38–40 of this long-term experiment indicate that CO_2 fluxes can decrease as tillage intensity decreases from MP to NT management. The increase in CO_2 fluxes from NT to MP management was consistent across average daily, seasonal, annual, and 26-mo cumulative fluxes (Tables 3–4). In the five of nine sampling events where NT had the lowest fluxes, it was within one or two months of double disking which likely reflects the higher residue cover increasing water content and reducing soil temperature. For example, across the 26-mo measurement period, the CO_2 fluxes were in this order: MP>CP≈DD>NT. The changes in CO_2 fluxes under CP and DD tended to be between the system with the least disturbance (NT) and the highest disturbance (MP) management systems. The differences among tillage systems were probably due to differences in soil aggregation, water content, soil temperature, and residue cover. Indeed, for the same experiment an earlier study found that the mean weight diameter of water-stable aggregates differed in this order: NT≈DD>CP≈MP (Kibet et al., 2016). Soil aggregates are well-known to protect SOM from microbial activity. Thus, tillage, which breaks soil aggregates, can enhance the decomposition of organic matter (Six et al., 2000, 2002). Further, tillage moves crop residues below the soil surface. The combination of organic matter release from aggregates and movement of residues into the zone of microbial activity can thus lead to greater CO_2 fluxes from tilled soils based on our research data.

The significant differences in daily soil CO_2 fluxes occurred mostly during measurement dates when water content and temperature significantly differed among the tillage systems. We expected no-till to have consistently cooler temperatures and wetter soil than other tillage systems due to residue cover. This expectation only occurred consistently following corn, which has higher residue cover than soybean. Of note, the significant tillage system effects also occurred most frequently during the soybean phase (i.e., corn residue) and during the late part of the off-season to early portion of the in-season. In this region, rainfed corn produces about 10 Mg ha^{-1} of residue (Ruis et al., 2017) and soybean about 3 Mg ha^{-1} (Dagel et al., 2014). Thus, the higher residue cover from corn most probably increased tillage system effects on soil water and temperature more than that from soybean. For example, a study with different levels of corn residue cover in Kansas showed higher soil temperatures in late winter through early summer with 50% and 100% residue removal (Kenney et al., 2015). Corn and soybean yields in the present experiment tend to be higher under no-till (Jasa, personal communication, 2021). Thus, while residues tend to be higher under no-till, MP, CP, and DD alter the residue cover leading to approximate

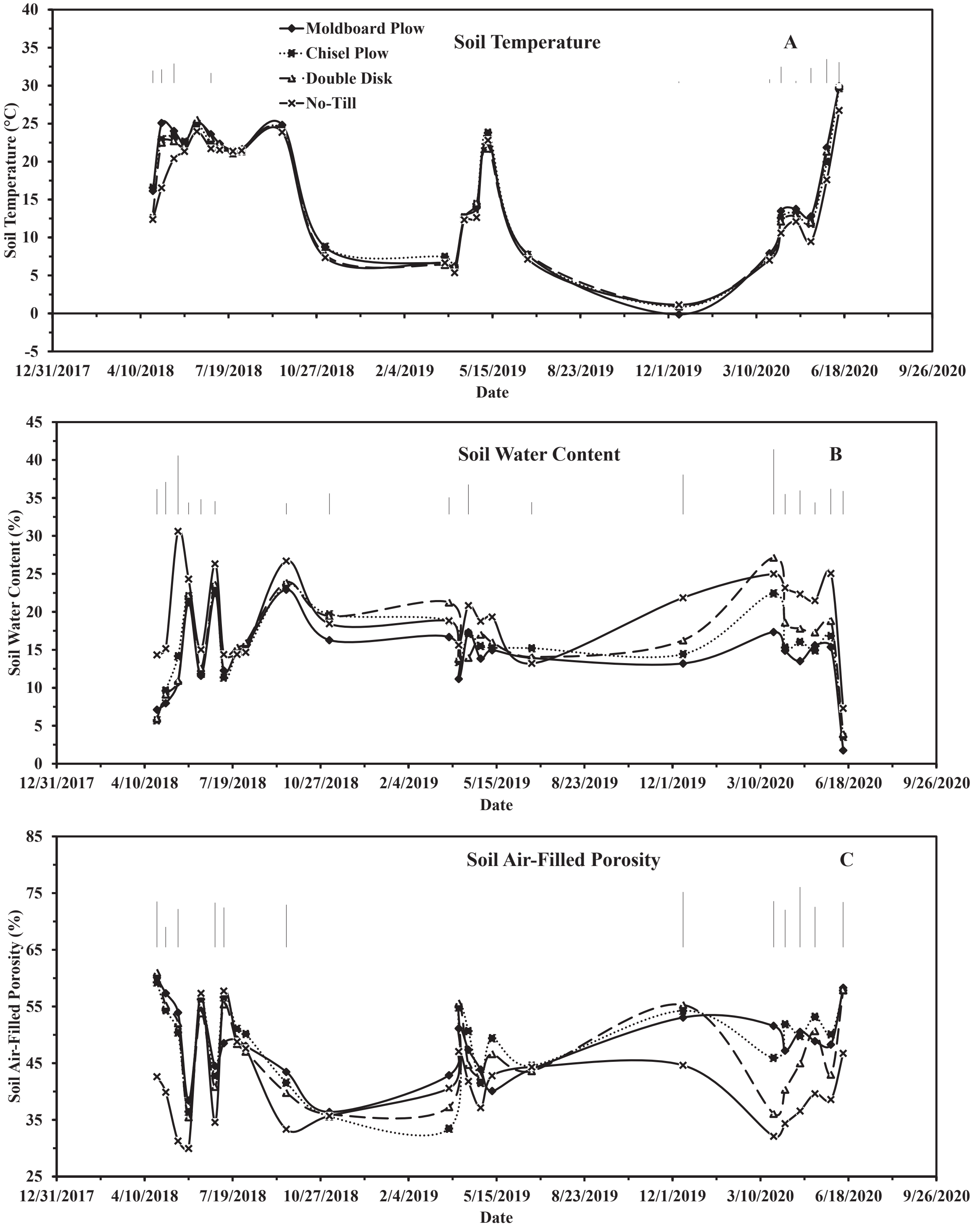

Fig. 3. Impact of 38–40 yrs of moldboard plow, chisel plow, double disk, and no-till on soil temperature (A), soil water content (B), and soil air-filled porosity (C) on 24 measurement dates between April 2018 and June 2020 from an experiment near Lincoln, NE. Lines above measurement dates are LSD comparisons for that date.

corn residue cover amounts in spring of about 10% for MP, 30% for CP, 30% for DD, and 90% for NT.

The decrease in CO_2 fluxes with NT in this long-term experiment agrees with that in our literature review (Table 6, Table S1). The literature review indicates that, of the 64 comparisons of NT against MP soils, MP increased CO_2 fluxes in 28, reduced in 18, and had no effect in 18 compared with NT. Similarly, of the 37 comparisons of NT against CP soils, CP increased CO_2 fluxes in 21, reduced in 4, and had no effect in 12 compared with NT. For disking vs NT, disking increased CO_2 fluxes in eight comparisons, reduced in one, and had no effect in five. The greater variability in effects of MP compared with CP and DD was likely the result of cropping system and soil texture. For example, regardless of tillage system, corn systems were more likely to show increased CO_2 fluxes with tilled systems (55% of comparisons) compared with NT while small grain systems may show increased (34% of comparisons) or decreased (47% of comparisons) CO_2 fluxes under tilled systems. Since our experimental data were under corn-soybean rotation, we would expect increased CO_2 fluxes under tilled systems based on the literature

Table 5

Correlations between soil gas fluxes and related soil properties during years 38–40 of a tillage experiment near Lincoln, NE. Gas fluxes and associated soil properties were determined between April 2018 and June 2020. Units for CO_2 fluxes were g m^{-2} d^{-1} for daily, and Mg ha^{-1} for seasonal, annual, and total. Units for N_2O and CH_4 fluxes were ng m^{-2} d^{-1} for daily, and g ha^{-1} for seasonal, annual, and total. * ** denotes significant at $p < 0.01$, * * at $p < 0.05$, and * at $p < 0.1$.

	CO_2-C	N_2O-N	CH_4-C	Soil Temperature (°C)	Soil Water Content (%)	Air-Filled Porosity (%)	Soil Organic C (g kg^{-1})	Total N (g kg^{-1})
Daily								
N_2O-N	-0.18 * **	1						
CH_4-C	0.18 * **	-0.73 * **	1					
Temperature (°C)	0.48 * **	0.17 * **	-0.14 * *	1				
Water Content (%)	ns	-0.14 * *	0.11 *	ns	1			
Air-Filled Porosity (%)	ns	ns	ns	ns	ns	1		
Soil Organic C (g kg^{-1})	-0.14 * *	ns	ns	ns	0.23 * **	-0.19 * **	1	
Total N (g kg^{-1})	-0.17 * **	ns	ns	ns	0.26 * **	-0.23 * **	0.98 * **	1
Particulate Organic Matter (g kg^{-1})	-0.14 * *	ns	ns	ns	0.26 * **	-0.31 * **	0.53 * **	0.66 * **
In-season 38								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	0.82 * **	ns	0.69 * *	1				
Water Content (%)	-0.75 * **	ns	ns	-0.83 * **	1			
Air-Filled Porosity (%)	0.70 *	ns	ns	0.83 * **	-0.90 * **	1		
Soil Organic C (g kg^{-1})	-0.69 * *	ns	ns	-0.49 *	0.55 *	-0.50 *	1	
Total N (g kg^{-1})	-0.79 * **	ns	ns	-0.60 * *	0.066 * *	-0.63 * *	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	-0.60 * *	-0.63 * *	ns	-0.68 * *	0.71 * **	-0.75 * **	0.53 *	0.66 * *
Off-season 38								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	ns	ns	ns	1				
Water Content (%)	ns	ns	ns	ns	1			
Air-Filled Porosity (%)	ns	ns	ns	0.57 *	ns	1		
Soil Organic C (g kg^{-1})	ns	ns	ns	ns	0.80 * **	ns	1	
Total N (g kg^{-1})	-0.56 *	ns	ns	ns	0.79 * **	ns	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	ns	ns	ns	ns	0.53 *	ns	0.53 *	0.66 * **
In-season 39								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	ns	-0.62 * *	ns	1				
Water Content (%)	ns	0.67 * *	ns	-0.51 *	1			
Air-Filled Porosity (%)	ns	-0.53 *	ns	0.69 * *	-0.86 * **	1		
Soil Organic C (g kg^{-1})	-0.66 * *	ns	ns	ns	ns	-0.53 * *	1	
Total N (g kg^{-1})	-0.75 * **	ns	ns	ns	0.58 * *	-0.63 * *	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	ns	ns	ns	ns	0.58 * *	ns	0.53 *	0.66 * *
Off-season 39								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	0.65 * *	-0.64 * *	ns	1				
Water Content (%)	-0.61 * *	ns	ns	-0.63 * *	1			
Air-Filled Porosity (%)	0.61 * *	ns	ns	0.53 *	-0.80 * **	1		
Soil Organic C (g kg^{-1})	-0.81 * **	ns	ns	-0.74 * **	0.58 * *	-0.51 *	1	
Total N (g kg^{-1})	-0.83 * **	ns	ns	-0.76 * **	0.61 * *	-0.62 * *	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	ns	ns	ns	-0.51 *	0.54 *	-0.80 * **	0.53 *	0.66 * *
Annual Cumulative Year 38								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	ns	ns	ns	1				
Water Content (%)	ns	ns	ns	ns	1			
Air-Filled Porosity (%)	ns	ns	ns	ns	ns	1		
Soil Organic C (g kg^{-1})	-0.67 * **	ns	ns	ns	0.65 * *	ns	1	
Total N (g kg^{-1})	-0.78 * **	ns	ns	ns	0.63 * *	ns	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	-0.45 *	ns	ns	ns	0.56 *	ns	0.53 *	0.66 * *
Annual Cumulative Year 39								
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	0.58 * *	-0.55 *	ns	1				
Water Content (%)	ns	ns	ns	-0.79 * **	1			
Air-Filled Porosity (%)	ns	ns	ns	0.59 * *	-0.86 * **	1		
Soil Organic C (g kg^{-1})	-0.59 * *	ns	ns	-0.72 * **	0.69 * *	-0.52 *	1	
Total N (g kg^{-1})	-0.69 * *	ns	ns	-0.75 * **	0.76 * **	-0.60 * *	0.97 * **	1
Particulate Organic Matter (g kg^{-1})	ns	ns	ns	-0.52 *	0.76 * **	-0.70 * *	0.53 *	0.66 * *
26-Mo Monitoring Period								

(*continued on next page*)

Table 5 (*continued*)

	CO_2-C	N_2O-N	CH_4-C	Soil Temperature (°C)	Soil Water Content (%)	Air-Filled Porosity (%)	Soil Organic C (g kg^{-1})	Total N (g kg^{-1})
N_2O-N	ns	1						
CH_4-C	ns	ns	1					
Temperature (°C)	0.71 * **	ns	0.70 * *	1				
Water Content (%)	-0.75 * **	ns	-0.54 *	-0.87 * **	1			
Air-Filled Porosity (%)	0.64 * *	ns	0.61 *	0.89 * **	-0.92 * **	1		
Soil Organic C (g kg^{-1})	-0.68 * **	ns	ns	-0.51 *	0.66 * *	-0.52 *	1	
Total N (g kg^{-1})	-0.80 * **	ns	ns	-0.64 * *	0.75 * **	-0.65 * *	0.98 * **	1
Particulate Organic Matter (g kg^{-1})	-0.60 * *	ns	-0.80 * *	-0.70 * **	0.75 * **	-0.85 * **	0.53 *	0.66 * *

Table 6

Summary of literature review of tillage system impacts on soil CO_2-C, N_2O-N, and CH_4-C fluxes on daily, seasonal (in-season is during crop growing period; off-season is non-crop growing period), and cumulative basis. Tillage systems are moldboard plow (MP), chisel plow (CP), disk (D), and no-till (NT).

Gas Flux	Tillage Comparison	Total Comparisons	Effect of Tillage Compared with NT
CO_2-C	MP vs NT	64	MP increased in 44%, reduced in 28%, and had no effect in 28%
	CP vs NT	37	CP increased in 57%, reduced in 11%, and had no effect in 32%
	D vs NT	14	D increased in 57%, reduced in 7%, and had no effect in 36%
N_2O-N	MP vs NT	40	No effect
	CP vs NT	23	
	D vs NT	8	
CH_4-C	MP vs NT	24	No effect
	CP vs NT	11	
	D vs NT	3	DD increased

review. Likewise, coarse- (55% of comparisons) and medium-textured (55% of comparison) soils were more likely to show increased CO_2 fluxes in tilled systems as opposed to NT whereas fine-textured soils may show increased (34% of comparisons) or no effect of among tillage systems (42% of comparisons). In our long-term experiment, the soil texture was a silty clay loam and showed increased CO_2 fluxes with tillage. Thus, our experimental data align with the literature review.

Long-term studies evaluating how an increase in tillage intensity affects CO_2 fluxes under a gradient of tillage systems within the same experiment are very few (Omonode et al., 2007; Ussiri and Lal, 2009; Guardia et al., 2016). The few studies showed either similar or contrasting effects of increasing tillage intensity compared with our long-term experimental data. For example, in a semiarid sandy loam soil under small grains, differences in tillage intensity (MP, CP, and NT) had no effect on CO_2 fluxes (Guardia et al., 2016), suggesting under relatively dry conditions (semiarid) and soils with lower potential for aggregation (sandy loam), tillage systems may not have a large effect on CO_2 fluxes. The opposite may be true in some wetter locations, such as temperate climates of the USA. For example, in a temperate silt loam under corn, differences in tillage intensity affected CO_2 fluxes in this order: MP≈CP>NT (Ussiri and Lal, 2009). In a temperate silty clay loam, under corn-soybean, tillage intensity affected CO_2 fluxes in this order: CP>MP≈NT (Omonode et al., 2007), which indicate that CO_2 fluxes among tillage systems may not always differ. The lower percentage of increases under MP in some cases, such as in the latter study, could be attributed to conditions during tillage operations (Omonode et al., 2007) or the burying of labile soil organic C (Quincke et al., 2007). For example, high water content and low temperature conditions may reduce the effects of MP as compared with CP (Omonode et al., 2007).

Most comparisons of NT vs tillage in our literature review were short-term studies of ≤ 5 yr (59 of 114 comparisons). Very long-term comparisons (>20 yr) were few (20 of 114). Of the very long-term comparisons, four reported daily fluxes, four reported cumulative, nine reported in-season fluxes, and three reported off-season fluxes. However, even fewer of these very long-term studies reported CO_2 fluxes across a gradient of tillage intensities for comparison with our results. Our daily and average annual cumulative CO_2 fluxes are within the range observed by Ussiri and Lal (2009). Similarly, our in-season fluxes were in-line with those reported by Omonode et al. (2007). In summary, both the literature review and experimental data show that NT can generally reduce CO_2 fluxes compared with tilled systems.

4.2. N_2O and CH_4 fluxes

Unlike CO_2 fluxes, tillage system did not affect daily N_2O fluxes or any cumulative fluxes calculated on the bases of in-season, off-season, annual, or total fluxes over 26 months. We did observe uptake of N_2O in late summer to early fall of year 38, when water content was high and soybean was maturing. High soil water content and low water use by the crop may have stimulated complete denitrification of NO_3 to N_2, which can also consume N_2O when denitrification activities are very high (Chapuis-Lardy et al., 2006). Nitrogen fertilization rate is a driver of N_2O fluxes, thus the lack of differences in N_2O fluxes among the different tillage systems could be attributed to all treatments receiving the same N-fertilization rate. Had the experimental design included an N fertilization rate, it is possible we would have observed a tillage × N rate interaction as suggested by Venterea and Stanenas (2008). Also, N_2O emissions were low, thus tillage system effects may have been difficult to detect due to spatial and temporal variation. Our experimental results of tillage system effects on N_2O fluxes were similar to our literature review across all time periods (daily or short-term, in-season, off-season, and annual cumulative) where 37 of 69 comparisons showed no effect of tillage system on N_2O fluxes, 18 reported decreased, and 14 reported increased (Table 6, Supplementary Table S.2). In other words, the review data show that MP may have no effect on N_2O fluxes in 46% of comparisons, CP in 55%, and DD in 88% relative to NT. This suggests that MP and CP may have more variable effects on N_2O fluxes than DD probably due to the volume of soil disturbed and the wide range of microsites produced by MP and CP. There was no effect of tillage system on N_2O fluxes regardless of examining the data by cropping system and other factors. In sum, tillage system has minimal effects on N_2O fluxes based on both our experimental data and published literature.

Similar to N_2O fluxes, the effect of tillage system on CH_4 fluxes was minimal on a daily basis and resulted in no effects on in-season, off-season, annual cumulative, or total cumulative fluxes (Table 6, Supplementary Table S.3). Similar to our data, the review of literature showed that, across all time periods, CH_4 fluxes were unaffected by tillage system in 21 of 38 comparisons, increased in 13, and decreased in 4. This indicates that MP and CP may have no effect on CH_4 fluxes in 55% of cases. Disking, however, increased CH_4 fluxes in our review unlike in our experiment, which found no effects. The findings from our experimental data and literature suggest tillage system may have minimal effects on CH_4 fluxes similar to effects on N_2O fluxes.

4.3. Relationships among factors and soil gas fluxes

The negative correlations of CO_2 fluxes with water content, soil organic C concentration, and particulate organic matter concentration suggest that increasing water content and soil organic C and particulate organic matter concentrations can reduce CO_2 fluxes (Fig. 4, Table 6), which is particularly evident between MP and NT (Fig. 4). The negative correlation between CO_2 fluxes and water content was expected as soils with higher water content have less air-filled pore space for gas exchange (i.e., positive correlation between CO_2 fluxes and air-filled pore space, Table 5). The negative correlations among CO_2 fluxes and soil organic C and particulate organic matter concentrations were unexpected because the more soil C, the more microbially active the soil will tend to be. The negative correlations were probably the result of long-term soil C loss and low aggregation, which can lead to higher CO_2 fluxes. For example, Kibet et al. (2016) for the same experiment reported lower soil C and soil aggregate size under MP and CP than NT for the 0–10 cm depth. Further, conventional tillage is well-known to disrupt soil aggregates, leaving crop residues and organic matter available to soil microbes rather than protected within soil aggregates (Six et al., 2000, 2002; Kibet et al., 2016; Jin et al., 2021). Also, movement of residues below the soil surface brings those residues in direct contact with soil microorganisms. Therefore, the combination of tillage-induced disturbance and movement of residues below the soil surface increased CO_2 fluxes under tillage compared to no-till. Of note, under no-till conditions, belowground biomass inputs to organic matter can range from 10% to 24% while aboveground biomass inputs to organic matter are substantially less at 0.5–1% (Mazzilli et al., 2015). Even under tilled conditions, root-based C dominates soil C (Puget and Drinkwater, 2001; Kong et al., 2010). The increased CO_2 fluxes with increasing temperatures were probably in part the result of increased soil microbial activity (Chavez et al., 2009; Ussiri and Lal, 2009).

The positive correlation between N_2O fluxes and temperature across the daily fluxes and the 26-mo measurement period indicates that as temperature increases, fluxes of N_2O also increase. The increase in N_2O with temperature was likely the result of greater biological activity (Ussiri et al., 2009). Of note, N_2O fluxes were negatively correlated with temperature during in-season year 39, off-season year 39, and annual cumulative fluxes during year 39, which indicates that as temperature increased, N_2O fluxes decreased. The negative relationship between N_2O fluxes and soil temperature during these time periods reflect lower activity of microbes involved in N_2O production under high temperatures. Methane fluxes were less correlated with soil properties that drive gas fluxes compared with the other GHG fluxes, which is expected as tillage system did not affect CH_4 fluxes. However, the negative correlation

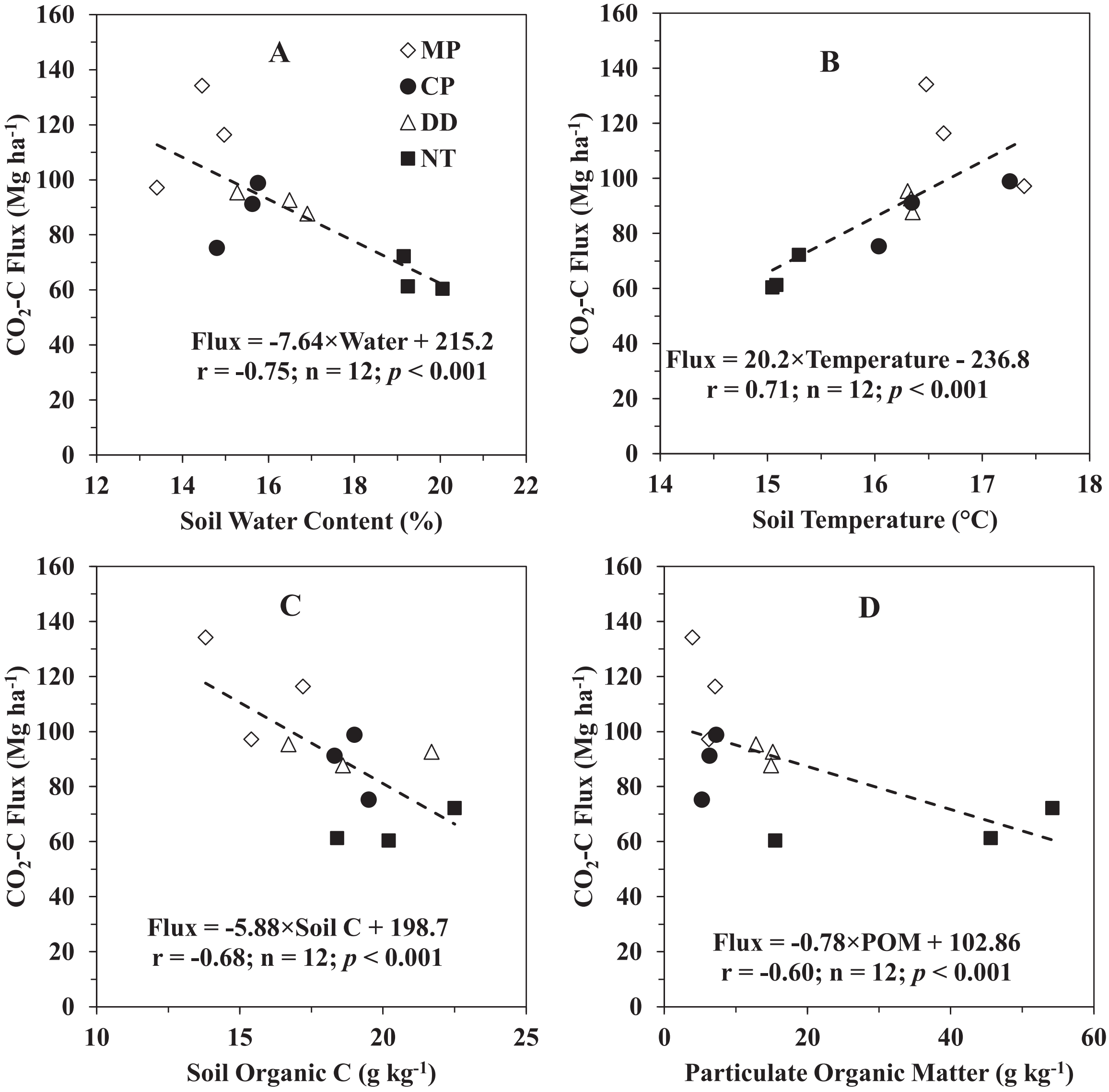

Fig. 4. Relationships of CO_2-C fluxes with soil water content (A), soil temperature (B), soil organic C concentration (C), and particulate organic matter concentration (D) during years 38–40 of an experiment near Lincoln, NE. MP = moldboard plow, CP = chisel plow, DD = double disk, and NT = no-till.

between CH_4 fluxes and temperature and positive correlation between CH_4 fluxes and water content likely indicate increasingly anaerobic conditions needed for methanogenesis. Note that in most upland, aerobic soils methane tends to be consumed rather than emitted (Le Mer and Roger, 2001).

5. Conclusions

This study evaluating the impacts of long-term (38–40 yr) tillage systems including MP, CP, DD, and NT indicates that CO_2 fluxes generally decreased under NT compared with tilled soils while N_2O and CH_4 fluxes were unaffected by tillage systems. These findings agree with those of our review of published literature. Results show that cumulative CO_2 fluxes decreased in this order: MP>CP≈DD>NT, which indicates that CO_2 fluxes decreased as tillage intensity decreased, probably due to increased water content and improved aggregate stability, which can protect organic C from microbial activities. These results further suggest that NT may store more soil C than tilled systems, particularly near the soil surface. Further, the reduction in CO_2 losses by NT indicates adoption of NT can reduce CO_2 fluxes. Soils under NT, thus, may capture and retain more of the atmospheric C in agricultural systems. The lack of significant impacts of tillage on fluxes of N_2O and CH_4 suggests that soil disturbance may have small or no effects on these fluxes relative to CO_2. Overall, based on the data from this long-term (38–40 yr) experiment and the global literature review, reducing or eliminating tillage can be a strategy to reduce losses of C as CO_2 although it may have limited or no effect on N_2O and CH_4 fluxes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2022.105359.

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