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Greenhouse Gas Fluxes and Soil Carbon and Nitrogen Following Single Summer Tillage Event

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Authors' contributions

This research was carried out in collaboration between authors. All authors designed the study. Authors PB and RG conducted the field experiment and laboratory analyses, and performed statistical analyses. Authors UN and JBN provided initial outline for the paper. All authors contributed to manuscript writing and formatting. Author UN was the principal investigator of the project that funded this experiment. All authors read and approved the final manuscript.

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ABSTRACT

No-till farming results in gradual buildup of soil organic matter (SOM) and re-introduction of tillage can often reverse it. However, tillage in low precipitation regions may be needed to manage weeds and disperse accumulation of immobile soil nutrients. The main objective of this study was to assess the effects of a single summer tillage on carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), soil water filled pore space (WFPS), dissolved organic carbon (DOC) and nitrate (NO_3) in winter wheat - summer fallow systems that were either tilled for the first time after nine years of no-till (NTT), not-tilled (no-till, NT) or were frequently tilled (conventional, CT; and organic, CF). The study was established in the US Central High Plains region where annual precipitation averaged 332±39 mm. Soil and gas samples were collected before the tillage event (time zero) and at 1hr, 5 hrs, 25 hrs and 50 hrs after. Immediate increases in CO_2 and N_2O fluxes were observed in all tilled treatments within the first 1 to 5 hours but 50-hr cumulative N_2O and CO_2 in NTT did not differ from

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the values observed in NT. Tillage however, resulted in a 22% greater 50-hr cumulative CH_4 assimilation in NTT compared with NT and was comparable with CH_4 in CT suggesting enhanced soil aeration. Soil NO_3 did not change in NTT unlike in CT and CF and soil DOC did not increase in NTT until 25 hrs after when, it returned to levels comparable with time zero. In contrast, DOC in CT and CF continued to stay elevated after 50 hrs. In conclusion, single tillage event of a long-term no-till performed on dry soil during summer did not negate benefits associated with SOM accrual and may be a viable alternative for farmers to address some of the management-related problems.

Keywords: Dry land farming; no-till; soil organic matter; dissolved organic carbon; nitrate; wheat-fallow system.

1. INTRODUCTION

Tillage during the fallow phase is a common practice in dry land winter wheat (*Triticum aestivum* L.) production in the US Central High Plains. Repeated tillage of marginally productive soils in this low precipitation region (annual precipitation ranging between 300 to 400 mm yr^{-1}) [1] has however, resulted in loss of soil organic matter (SOM) and decline in soil nutrient availability [2]. Conversely, long-term no-till management has helped accrue multiple agroecosystem benefits [2,3], which include increase in SOM, reduced soil erosion and improved soil profile water storage [4,5]. While producers who practice no-till in semi-arid regions are typically committed to this form of management, there are several reasons why occasional summer tillage may prove beneficial and offer solutions to some no-till related problems. For example, tillage can temporarily improve soil aeration [6], help incorporate crop residues, disperse near-soil-surface-accumulated low-mobility phosphorous (P) [7]; reduce soil compaction [8], control weeds [9] and reduce stratification of SOM [10].

Tilling of the dry soil however, can trigger microbial processes leading to SOM mineralization and greenhouse gas (GHG) emissions [11,12]. The mechanism of SOM decomposition starts with the release of newly formed or previously aggregate-protected labile organic substrates that are subsequently made available to soil microbes. This results in immediate production of carbon dioxide (CO_2) and nitrous oxide (N_2O), and increased assimilation of methane (CH_4). These rapid changes are important indices demonstrating early soil response to disturbance. In addition, these three gases are of particular interest as they affect soil carbon (C) and nitrogen (N) exchanges with the atmosphere [13] and are important players in the global C cycle [14]. Factors affecting SOM decomposition following disturbance include temperature, water, aeration, pH, and mineral nutrients, plant residue quality and soil structure [15]. For example, frequently tilled soils in semi-arid regions generate twice as much CO_2 compared with long-term not tilled soils over a period of the growing season [16].

CO_2, N_2O and CH_4 are of particular importance as potent GHG species. N_2O is produced primarily during the process of denitrification and carried out by anaerobic microorganisms ubiquitous in soils experiencing periodic water saturation [17]. The process of N_2O production however, is not limited to water-saturated soils, but also takes place in any soil where anoxic microsites exist [18]. In addition, N_2O is produced during aerobic nitrification in well-aerated soils [19]. A single rainfall event after prolonged periods of drought can trigger immediate N_2O pulses that can equal 80-90% of total annual N_2O emissions in semiarid native rangelands [20,21]. Similar water pulses can result in temporary increase in methanogenesis [14]. On the other hand, tillage can trigger CH_4 assimilation driven by methanotrophic microorganisms [14]. It is known that well drained soils effectively assimilate CH_4 and in general, dry soils are important sinks for atmospheric C [22].

The main objective of this study was to quantify GHG emissions and soil C and N after a single summer tillage event performed on a series of winter wheat fallows that have been tilled for the first time after nine years of no-till or are frequently tilled. Such information can help understand the SOM mineralization triggered by a tillage disturbance and demonstrate whether an occasional tillage jeopardizes long-accrued benefits of a no-till practice.

2. MATERIALS AND METHODS

2.1 Study Site

The experiment was conducted in July 2011 at the University of Wyoming Sustainable Agriculture Research and Extension Center (SAREC) near Lingle, WY (42º 5' N, 104º 23'W and 1314 meters elevation). Soils at the location are classified as loamy, mixed, active, mesic Ustic Torriorthents, with less than one percent SOM and slightly alkaline soil pH. Climate is semi-arid with approximately 125 frost-free days, average maximum and minimum temperatures of 17.9ºC and 0.2ºC, respectively, and average annual precipitation of 332±39 mm [1]. Two-week antecedent precipitation before the start of experiment amounted to 28 mm and no precipitation occurred during the five-day period prior to the experiment.

2.2 Experimental Design and Treatments

The experiment was established in a series of 5-ha fields under different long-term tillage treatments that were first applied in 2002. Fields were located adjacent to each other and positioned on a similar landscape. Treatments consisted of: first-time tillage after nine years of a no-till (NTT); no-till managed exclusively with chemicals for weed control (NT), a combination of tillage and chemical weed control also referred to as "conventional" (CT), and chemical-free frequently tilled organic system (CF) (Table 1). The CF treatment involved a maximum of six tillage operations per year and tillage was the only form of soil management and weed control. The CF treatment was designed to reflect organically certified wheat production in eastern Wyoming. This system relies on no external (fertilizer and herbicides) inputs and tillage frequency is determined based on need for weed control. The CT treatment involved a maximum of four tillage operations per year. Due to reoccurring plant-available water shortages, low fertility soils and low overall crop yields, no fertilizer was used in any of the systems. Spring and early summer tillage is replaced with herbicide applications. Early summer tillage operations to a depth of 15 cm in CF were performed using Krause tandem disk (Khun Krause Inc., Hutchinson, KS). Subsequent summer tillage operations to a depth of 10 cm were performed using a Sunflower Fallow-King® (Sunflower Manufacturing, Beloit, KS). Fertilizers have not been applied in any of the treatments since 2002.

Five 10 m × 10 m plots were established at randomly selected locations in NT, CT and CF treatments in fallow strips that were 60 meters long. The NTT plots were also established within the same fallow strips as NT plots. Constraining NTT plots to the same filed as NT treatment plots was intended to assure that concurrent GHG and soil measurements were performed within a

Table 1. Field operations for no-till (NT), first time tillage of no-till (NTT), conventional tillage (CT), and chemical-free (CF) systems in dryland wheat-fallow cropping systems until the start of experiment

Operation	Tillage treatment			
	NT	NTT	CT	CF
Tillage operations per year	-	-	up to 4 times	up to 6 times
Tillage equipment	-	Sunflower Fallow-King®	Krause Tandem Disk; Sunflower Fallow-King®	Krause Tandem Disk; Sunflower Fallow-King®
Herbicides per year	as needed	as needed	1 time	-
Type of herbicides	2,4-D; Thifensulfuron-methyl and Tribenuron-methyl; Glyphosate	2,4-D; Thifensulfuron-methyl and Tribenuron-methyl; Glyphosate	2,4-D; Thifensulfuron-methyl and Tribenuron-methyl; Glyphosate	-
Surface residue	>35%	<30%	<15%	<10%

comparable window of time. Individual plots representing NT and NTT were located at least 10 meters away from each other. Fallow strips in CT and CF were plowed two times in spring before the experiment (May and June 2011). One week prior to the experiment, all plots were staked out, locations marked using GPS and the polyvinyl chloride (PVC) rings (25 cm diameter x 10 cm high) were deployed in each plot by inserting them 7 cm deep in the soil. These rings served as bases for periodic GHG measurements.

2.3 Soil and Air Sampling

In the morning of July 19th, the first set of soil and air samples were taken (time zero,T0). Shortly after, PVC rings were removed from NTT, CT and CF plots, and plots were tilled with Sunflower Fallow-King® to a depth of 10 cm. Immediately following the tillage event, PVC rings were reinserted to the ground in the original locations and soil and GHG samples collected from all tilled and NT treatments. Measurements were taken at 1hr (T1), 5 hrs (T5), 25 hrs (T25), and 50 hrs (T50) after tillage. Soil and air temperatures were recorded at each time interval using a digital thermometer placed adjacently to the chambers.

Each time, GHG samples were obtained at 0, 15, and 30 min after deployment of chamber tops on the bases using an enclosure technique by Hutchinson and Mosier [23,24]. GHG samples were drawn using a 60-ml polypropylene syringe (Fisher Scientific Inc.), from which 30 ml of sample was flushed out and remaining 30-ml was injected into 12 ml pre-evacuated LabcoExetainer® glass vials sealed with rubber septa. In the lab, gas samples were analyzed using a Shimadzu GC-2014 Gas Chromatograph (Shimadzu, Kyoto, Japan) equipped with auto-sampler and thermal conductivity, flame ionization, and electron capture detectors to capture CO_2, CH_4 and N_2O, respectively. Fluxes were calculated from the change in GHG concentrations in the chamber headspace over time. Cumulative fluxes of individual gas species over 50-h period were determined by linearly interpolating hourly emissions and integrating the underlying area as described in Hutchinson and Mosier [25].

Concurrently with gas sampling, soil samples (0-10 cm) were collected from three random plot locations within a minimum distance of 0.5 meter away from GHG chamber bases. Three soil cores were homogenized, coarse fragments removed, and a single 5 g subsample was immediately field extracted with 50 ml of 2 molar potassium chloride (*2M* KCl). The remaining soil was bagged, stored in a cooler and transported to the lab for further analyses.

2.4 Laboratory Analyses

Soil water content was determined by the gravimetric technique [26], dissolved organic carbon (DOC) was quantified using a Shimadzu TOC Analyzer (TOC-VCPH, Shimadzu, Kyoto, Japan) and soil nitrate (NO_3) concentration was determined using a micro plate spectrophotometer (Biotek Inc.) [27].

A sub-set of soil samples collected at the beginning of the study was analyzed for particle-size distribution using the hydrometer method [28], bulk density by the core method [29], and pH and electrical conductivity by electrode [30]. Total C and total N (Total N) contents were determined by dry combustion using a NC-2100 elemental analyzer (Carlo Erba Instruments, Milan, Italy). Inorganic C was determined using the modified pressure-calcimeter method [31]. Soil organic C (SOC) was determined by subtracting inorganic C from total C. Water filled pore space (WFPS) was calculated from soil bulk density and gravimetric water content [32]. Particle density of 2.65 g m^{-3} was used in WFPS calculation.

2.5 Statistical Analyses

Data were analyzed using PROC MIXED in the Statistical Analysis System (SAS ver. 9.3, SAS Institute, Cary, NC) [33]. Plots within each treatment though spatially explicit and well replicated, were considered as pseudo-replicates. The statistical analysis considered treatment as a fixed term, time of sampling as a repeated measure, and replications as random terms in the statistical model. The cumulative CO_2, CH_4, and N_2O fluxes were analyzed using one-way ANOVA. Means were separated using PDIFF test in the LSMEANS procedures. Treatment effects were considered significant at $P \leq 0.05$. Change in WFPS over time was analyzed using (PROC REG) in SAS. Regression analyses were performed to compare slopes representing change in WFPS over time.

3. RESULTS

3.1 Baseline Soil Properties

Soils at the location were comparable among the treatments and classified as sandy loams. Soils had BD 1.37 g cm^{-3}, EC 0.97 ds cm^{-1}, pH 8.64, and IC 2.70 g $kg^{-1.}$ Soil in NT and NTT had comparable Total N, which was 36% and 34% higher than in CT and CF, respectively (Table 2). In addition, NT and NTT had 17% and 12% higher SOC content than CT and CF. Soil and air temperatures during the experiment were high and ranged between 27ºC and 40ºC.

3.2 Water Filled Pore Space

Soil WFPS showed significant effects of tillage ($P\leq 0.02$) and time ($P<0.001$) but no tillage x time interaction. The highest WFPS was reported in NT and the lowest in CF soils. There were however, differences between regression slopes representing WFPS response to tillage treatments in time (Fig. 1). While NT soil was losing soil water at a rate of 0.09% per hr, water loss in NTT soils was only 0.03% higher, while loss in most frequently tilled CF soils were the highest and amounted to 0.20% per hr, respectively.

3.3 Carbon Dioxide

Carbon dioxide showed significant treatment x time interaction ($P\leq0.001$). Before tillage, CO_2 fluxes in NTT did not differ from fluxes in NT and CT but were significantly (33%) smaller than in CF (Fig. 2a). Within the first hour, CO_2 in NTT increased from 10.7 mg C m^{-2} hr^{-1} to 25.6 mg C m^{-2} hr^{-1} which was 68% more than CO_2 flux in NT at T1". CO_2 flux in NTT was comparable with CF and 22% lower than in CT. The CO_2 flux in NTT was, however, short-lived and became comparable with flux observed at T0 within five hrs. In contrast, CO_2 in CT and CF at T1 and T5 were 25% and 67% greater compared with T0. These two fluxes declined to levels comparable with T0 after 25 hrs. The 50-hr cumulative CO_2 in NTT averaged 591 mg C m^{-2} and was not significantly different than cumulative CO_2 in NT (555 mg C m^{-2}). It was however; significantly lower than CO_2 in CF (983 mg C m^{-2}) and CT (921 mg C m^{-2}).

3.4 Methane

Methane also showed significant treatment x time interaction ($P\leq0.001$). All treatments had comparable CH_4 assimilation at T0 that averaged 7.0 µg C m^{-2} hr^{-1} (Fig. 2b). At T1, the CH_4 assimilation in NTT doubled compared with T0, and it was significantly greater than NT and CF but similar to CH_4 assimilation in CT. This increase in NTT was, however, short-lived and the CH_4 assimilation became comparable with T0 in NT after five hrs. The 50-hr cumulative CH_4 assimilation in NTT (540 µg C m^{-2}) was 28% greater than in NT, 22% greater than in CF but 16% lower than CH_4 in CT.

3.5 Nitrous Oxide

Nitrous oxide also showed significant treatment x time interaction ($P\leq0.001$). All treatments had comparable N_2O fluxes at T0 (Fig. 2c). Tillage did not generate an initial N_2O pulse in NTT at T1 unlike in CF and CT when N_2O increased by 122% and 65%, respectively. On contrary, the N_2O flux in NTT was significantly reduced (20%) in T1 compared with T0 (37.2 µg N m^{-2} hr^{-1}).

3.6 Soil Dissolved Organic Carbon

Soil DOC also demonstrated significant treatment x time interactions ($P\leq0.05$). Before tillage, all treatments had comparable DOC (Table 3). At T1, DOC in CT and CF was significantly greater compared with values in NTT and NT. At T25 however, DOC in NTT became significantly greater than in NT and CT but comparable with CF. Twenty five hrs later at T50, DOC became significantly lower in CT and CF compared with NT and NTT. Soil DOC in NTT and NT did not change following tillage except for T25 when DOC in NT was significantly lower than at T0.

3.7 Soil Nitrate

Soil NO_3 at T0 was comparable among NTT, CF, and NT, and they were significantly lower than in CT (Table 3). Tillage did not increase NO_3 in NTT at T1 or thereafter, unlike in CT and CF where it increased by 4.04 and 4.92 mg kg^{-1} to values that were significantly greater than in NT and NTT. Nitrate remained elevated in CT and CF until T50. Nitrate in NT at T50 was significantly greater compared with T0, but the values were lower than NO_3 in CT and CF and comparable with NTT.

Table 2. Soil (0-10 cm depth) total nitrogen (Total N); organic carbon (SOC), and inorganic carbon (IC), pH, electrical conductivity (EC), bulk density (BD) and texture in no-till (NT), no-till tilled for the first time (NTT), conventional tillage (CT) and chemical-free (CF) dry land winter wheat-fallow systems. Values in parentheses indicate standard errors (n = 5). Same letters within each row indicate no significant difference among management practices (at minimum P<0.05)

Parameters	**Management practices**			
	NT	**NTT**	**CT**	**CF**
Total N (g kg^{-1})	0.81(0.20)a	0.88(0.13)a	0.54(0.05)b	0.56(0.22)b
SOC (g kg^{-1})	5.08(0.21)a	5.22(0.62)a	4.27(0.35)b	4.56(0.39)b
IC (g kg^{-1})	2.85(0.27)	2.68(0.27)	2.90(0.31)	2.35(0.10)
pH	8.70 (0.05)	8.70(0.07)	8.62(0.03)	8.60(0.03)
EC (ds cm^{-1})	0.97(0.03)	0.97(0.02)	0.97(0.02)	0.96(0.01)
BD (g cm^{-3})	1.38(0.02)	1.37(0.02)	1.36(0.02)	1.37(0.02)
Sand (%)	62.4(1.03)	61.2(1.39)	61.2(0.58)	60.0(1.22)
Silt (%)	30.2(0.49)	31.0(1.52)	32.2(0.37)	32.6(0.93)
Clay (%)	7.40(1.03)	7.80(0.20)	6.60(0.24)	7.40(0.60)
Soil Texture	Sandy loam	Sandy loam	Sandy loam	Sandy Loam

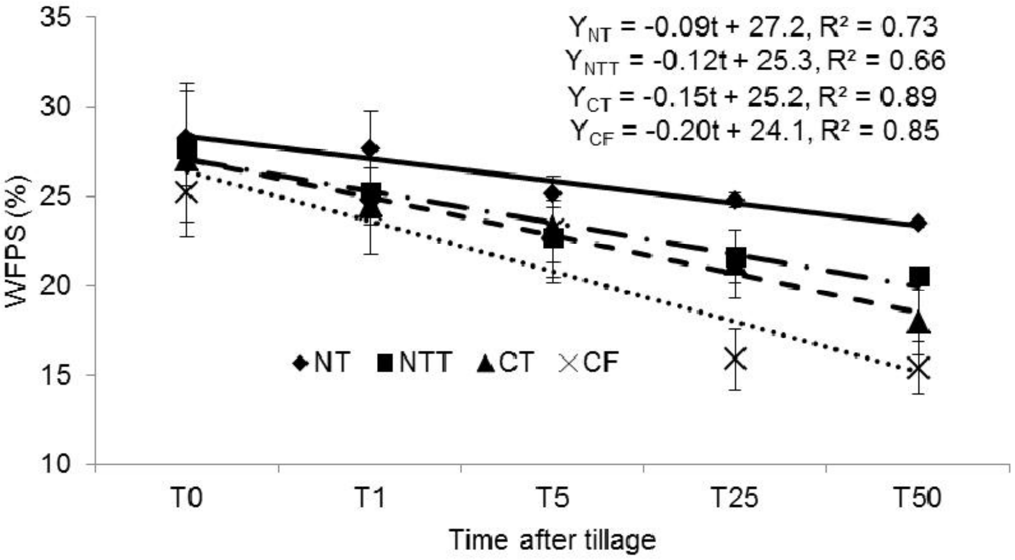

Fig. 1. Water filled pore space (%) in no-till (NT), no-till tilled for the first time (NTT), conventional (CT), and chemical-free (CF) systems at times zero (T0), one (T1), five (T5), 25 (T25) and 50 (T50) hours after tillage. Bars indicate mean standard errors (n = 5). Lines indicate regression lines for individual treatments

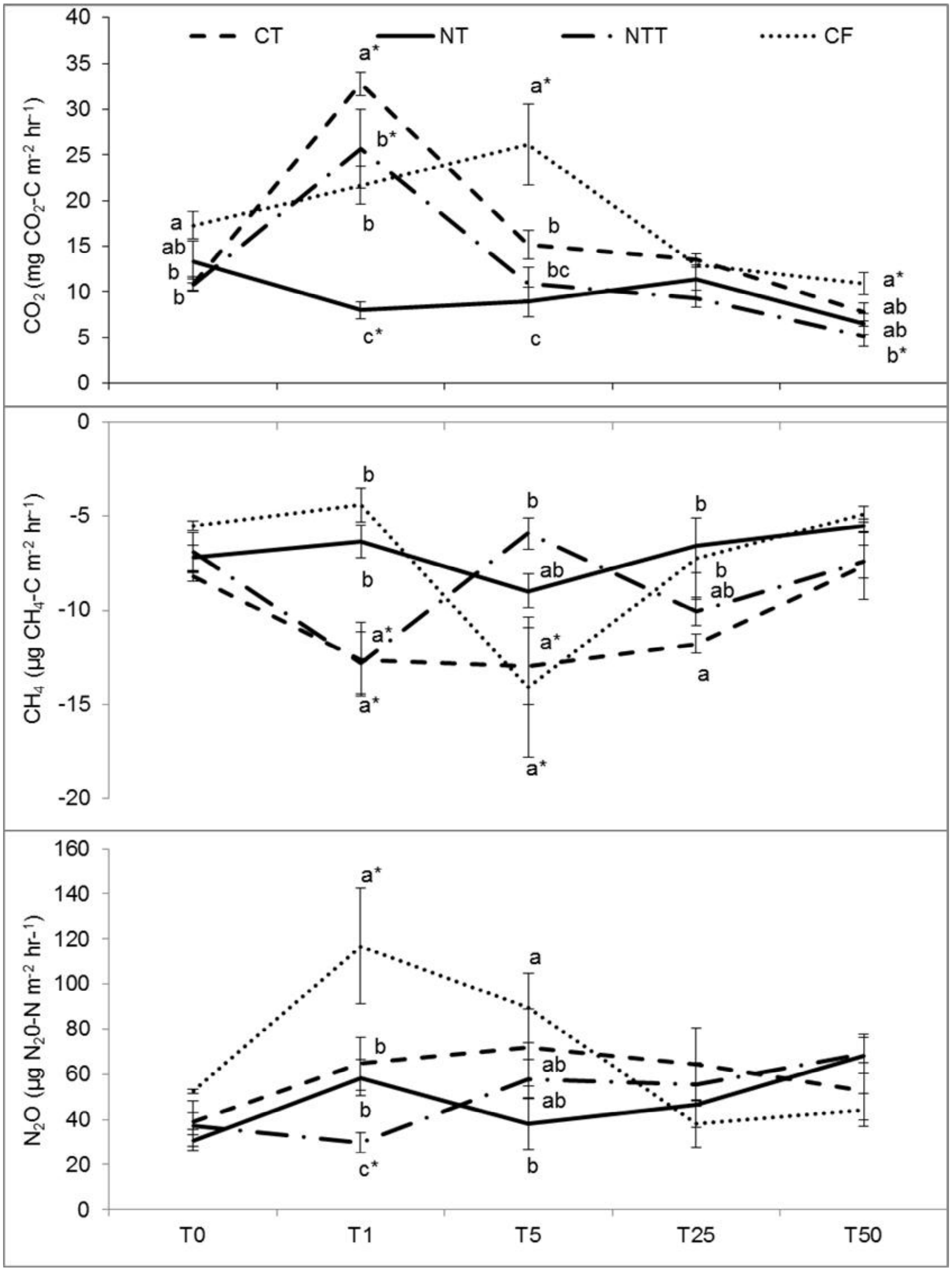

Fig. 2. Carbon dioxide (CO_2) (a), methane (CH_4) (b) and nitrous oxide (N_2O) (c) fluxes from no-till (NT), no-till tilled for the first time (NTT), conventional (CT), and chemical-free (CF) systems times zero (T0), one (T1), five (T5), 25 (T25) and 50 (T50) hours after tillage. Bars indicate standard errors (n = 5). Lower case letters indicate significant treatment differences in each time ($P \leq 0.05$). Asterisk (*) indicates significant differences in time within each treatment

Table 3. Dissolved organic carbon (DOC) and soil nitrate (NO_3) at time zero (T0), and at one (T1), five (T5), 25 (T25) and 50 (T50) hours after tillage, in no-till (NT), no-till plots tilled for the first time (NTT), conventional tillage (CT), and chemical-free (CF) management systems. †Values in parenthesis indicate standard errors (n=5). Lower case letters within each row indicate significant treatment differences (P≤0.05). Asterisk (*) within each column indicate significant differences between times within each treatment

Soil parameters	Hours after tillage	Management practice			
		NT	NTT	CT	CF
DOC (mg kg^{-1})	T0	123.5(5.4)	114.7(7.8)	119.9(7.0)	124.9(5.5)
	T1	117.7(5.1)b	115.1(7.3)b	132.9(8.6)a	141.1(3.2)a
	T5	113.8(3.4)	110.1(6.8)	120.5(6.7)	114.1(5.9)
	T25	103.9(2.7)c*	129.9(6.6)ab	127.0(6.8)b	145.3(7.8)a*
	T50	113.6(5.6)a	108.6(4.9)a	89.4(9.9)b*	102.8(5.9)ab*
NO_3 (mg kg^{-1})	T0	2.43(0.89)b	1.77(0.54)b	8.16(0.48)a	3.83(1.05)b
	T1	3.51(0.53)c	1.81(0.39)d	12.2(1.0)a*	8.75(0.50)b*
	T5	4.53(1.29)a	2.32(0.35)b	7.01(1.38)a	7.04(1.47)a*
	T25	4.13(0.45)b	3.86(1.06)b	7.64(1.06)a	6.56(0.84)a
	T50	5.34(0.37)b*	4.25(1.36)b	8.68(0.94)a	8.80(2.07)a*

4. DISCUSSION

Results from this experiment suggest that a single tillage performed during warm summer on previously not tilled dry soils had an insignificant impact on soil C and N as demonstrated by the lack of difference in cumulative CO_2 and N_2O fluxes between NTT and NT. These fluxes were also significantly lower than CT and CF despite higher overall soil Total N and SOC contents. Tillage however, did result in an immediate but short-lived CO_2 pulse in all tilled treatments including NTT, but the magnitude of initial CO_2 flux in NTT was only one-third of that from CT and CF. Elevated GHG fluxes from frequently tilled CT and CF soils further confirmed that repetitive tillage contributes to SOM mineralization [16,34]. It is likely that the initial CO_2 pulse in NTT was attributed more to the release of CO_2 trapped in soil pores under non-tilled soil surface as proposed by Kessavalou et al. [35].

Greater WFPS loss in CT and CF than in NT and NTT over time indicated greater soil water retention under the long-term no-till system, which was conserved even after a single tillage. One-time tillage in NTT also had no significant impact on soil DOC. Unlike CT and CF, where concentrations were initially greater but then significantly declined between 25 and 50 hrs to below NT and NTT levels. Al-Kaisi et al. [36] and Reicosky et al. [37] attributed these changes to soil aggregate disruption and exposure of aggregate-protected C to microbial activity. This newly released C was likely utilized as a microbial substrate during respiration or in support of microbial biomass as proposed by Norton et al. [21] and Ghimire et al. [38] and not measured in this study.

Interestingly, tillage resulted in an initial decline in N_2O fluxes within 1 hr after the event in NTT only. This observation agreed in part with the findings by Kessavalou et al. [35] who reported flux declines in frequently tilled soils as well. Moreover, the magnitude of the decline in NTT was much lower compared to the other study in which 83% reduction in N_2O for the period of two hours after tillage was observed in spring and 64% reduction for the period of 0.5 hr was observed in summer.

Less NO_3 in NTT compared with CT and CF suggested that a single tillage did not trigger anticipated N mineralization as often observed in less water limited agroecosystems [34]. In addition, nitrification was likely the process of N_2O production in the studied soils as previously proposed by Grandy and Robertson [39]. This was demonstrated by the synchrony between N_2O fluxes and soil NO_3 concentrations in CT and CF soils.

However, one-time tillage of a no-till increased soil aeration and allowed for a very short- lived (observed at T1 only) increase in CH_4 assimilation. Similar increases in assimilation were also observed as early as 30 min after tillage in wheat-fallow systems in the same region [35]. Such response suggested greater gas exchange between soil and atmospheric air and enhanced activity of methanotrophic microorganisms living in a soil layer below top 0-10 cm [40].

5. CONCLUSION

Our study suggested that single summer tillage performed for the first time in nine years in the dry and cold agroecosytem of the central High Plains did not negate the benefits of long-term no-till. Therefore, a summer tillage performed as needed, every several years can be a useful management tool for no-till dry land farmers. However, as soil moisture retention is very critical for dry land production, caution should be applied on how to schedule the timing of such operation. Even small water loss can have long-lasting consequences affecting crop yield in low precipitation regions. Additional research is needed to determine best tillage strategies (depth, intensity, spatial extend and the level of disturbance) to help advance our understanding of the effects of periodic tillage on soil properties and agroecosystem sustainability.

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COMPETING INTERESTS

Authors would like to declare that there were no competing interests of any nature in this research article and that each author played the stipulated roles in the process towards the success of this manuscript.

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