Fallow Effects on Soil Carbon and Greenhouse Gas Flux in Central North Dakota

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The inclusion of cover crops during fallow (i.e., green fallow) may mitigate greenhouse gas (GHG) emissions from dryland cropping systems. An investigation was conducted to quantify the effects of chemical and green fallow on soil organic C (SOC) and CO_2, CH_4, and N_2O flux within spring wheat (*Triticum aestivum* L.)–fallow (chemical fallow) and spring wheat–safflower (*Carthamus tinctorius* L.)–rye (*Secale cereale* L.) (green fallow) under no-till management in west-central North Dakota. Using static chamber methodology, flux measurements were made during 19 mo of the fallow period of each cropping system. Soil samples collected before initiation of flux measurements indicated no difference in SOC in the surface 10 cm between cropping systems. Additionally, differences in gas flux between cropping systems were few. Emission of CO_2 was greater under green fallow than chemical fallow during spring thaw until the termination of rye ($P = 0.0071$). Uptake of atmospheric CH_4 was the dominant exchange process during the evaluation period, and was significantly ($P = 0.0124$) greater under chemical fallow (-2.7 g CH_4–C ha^{-1} d^{-1}) than green fallow (-1.5 g CH_4–C ha^{-1} d^{-1}) following the termination of rye. Cumulative fluxes of CO_2, CH_4, and N_2O did not differ between the chemical- and green-fallow phases during the 19-mo period ($P = 0.1293$, 0.2629, and 0.9979, respectively). The results from this evaluation suggest there was no net GHG benefit from incorporating a rye cover crop during the fallow phase of a dryland cropping system under no-till management.

Abbreviations: GHG, greenhouse gas; POM, particulate organic matter; SOC, soil organic carbon; WFPS, water-filled pore space.

Quantifying GHG flux from dryland cropping systems is necessary to better understand agriculture's effect on global environmental quality. Within the northern Great Plains of North America, dryland cropping systems are prevalent, as the region's dry and cool continental climate has afforded suitable conditions for growing a broad portfolio of annual crops (Padbury et al., 2002). While changes in SOC under a spectrum of dryland cropping systems have been documented for the region (Janzen et al., 1998; Liebig et al., 2005), relatively little is known about management influences of cropping intensity, tillage, and N fertility on CO_2, CH_4, and N_2O fluxes.

Among the management options available to agricultural producers in the northern Great Plains, the use of fallow has persisted despite documented drawbacks of reduced precipitation-use efficiency and impaired soil quality compared with annually cropped land (Farahani et al., 1998; Wienhold et al., 2006). Fallow periods are common throughout the region due to the absence of consistent precipitation, and may occupy up to 35% of cropland area in any given year (Padbury et al., 2006). While the use of fallow has decreased steadily since the 1980s (Lubowski et al., 2002), production uncertainties associated with future climate

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change may result in continuation of this practice throughout the region.

Little is known regarding the effects of fallow on GHG flux in the northern Great Plains. Carbon dioxide emission has been found to be lower in cropping systems with the inclusion of fallow due to lower C inputs (Akinremi et al., 1999; Curtin et al., 2000), with emission profiles strongly influenced by soil temperature (Frank et al., 2006). Fallow may enhance the capacity of the soil to act as a sink for CH_4 (Mosier et al., 1991), but measured uptake rates have been small (1.8–7.4 g CH_4–C ha^{-1} d^{-1}) (Mosier et al., 1991; Kessavalou et al., 1998). The effects of fallow on N_2O emission in the region have been mixed. Greater N_2O emission has been observed under fallow relative to cropped phases when no N is applied (Mosier et al., 1991; Lemke et al., 1999). Conversely, when N is applied, N_2O emission during fallow has been found to be lower than during cropped phases (Dusenbury et al., 2008).

Despite the lack of information on GHG flux in fallow, management strategies are needed to limit emissions during this critical non-cropping phase (Barton et al., 2008). Among the options available to producers include the use of cover crops. When grown individually or in mixtures, cover crops have been shown to benefit agronomic performance and environmental quality within established cropping systems by improving soil quality and erosion control and decreasing losses of N (Francis et al., 1998; Dabney et al., 2001; Snapp et al., 2005). These benefits may translate to lower GHG emissions through decreased N loss as N_2O and increased SOC from organic matter inputs (Grant et al., 2002). Given this context, the objective of this study was to contrast fallow phases in two cropping systems for their effects on SOC and CO_2, CH_4, and N_2O flux. One cropping system possessed a traditional 19-mo fallow period (spring wheat–fallow [SW-F], chemical fallow), while the other incorporated a rye cover crop during the non-cropping period (spring wheat–safflower–rye [SW-S-F (rye)], green fallow).

MATERIALS AND METHODS

Site and Treatment Description

The experimental site was located within the Missouri Plateau approximately 6 km south of Mandan, ND (46°46'12" N, 100°54'57" W) on Field H3 of the Area IV Soil Conservation District Cooperative Research Farm. The site is on gently rolling uplands (0–3% slope) with a silty loess mantle overlying Wisconsin-age till. The predominant soil at the site is a Temvik–Wilton silt loam (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). From 1914 to 2005, annual precipitation averaged 407 mm, with >75% of the total received during the growing season from April through September. The average annual temperature is 4°C, although daily averages range from −11°C in the winter to 21°C in the summer.

Treatments evaluated in the study were part of a long-term cropping system experiment established in 1993 (reviewed by Liebig et al., 2004). Of the 12 treatment combinations included in the experiment, two were evaluated: SW-F and SW-S-F(rye). Both crop sequences were managed using no-till, so the soil was disturbed only at planting. Each phase of both crop sequences was present every year and treatments were replicated three times. Individual plot size was 9.1 by 30.1 m. Nutrient and weed management of the treatments included spring fertilization of 67 kg N ha^{-1} (as NH_4NO_3 for 1993–2001, urea thereafter) after a crop and 34 kg N ha^{-1} after fallow, along with 11 kg P ha^{-1} (as triple superphosphate) with the seed at planting. No N or P was applied before the fallow phase. Weeds were managed using herbicides based on recommended practices used by area producers. Spring wheat in SW-F was harvested on 4 Aug. 2006. The rye cover crop in SW-S-F(rye) was seeded on 29 Sept. 2006 at 3.2 million viable seeds ha^{-1} using a Haybuster 8000 drill (DuraTech Industries Int., Jamestown, ND). The rye crop was killed at anthesis (14 June 2007) using glyphosate [*N*-(phosphonomethyl) glycine] and dicamba (3,6-dichloro-2-methoxybenzoic acid) at rates of 1.36 and 0.42 L a.i. ha^{-1}, respectively.

Soil Sampling Protocol and Analysis

Soil samples were collected on 10 Oct. 2006 in all crop phases of both treatments. Ten soil cores were collected in each plot from two depths, 0 to 5 and 5 to 10 cm, using a 3.5-cm (i.d.) step-down probe and composited by depth. Each sample was saved in a double-lined plastic bag, placed in cold storage at 5°C, and analyzed within 4 wk of collection.

Soil samples were processed by drying at 35°C for 3 to 4 d and then ground by hand to pass a 2.0-mm sieve. Identifiable plant material (>2.0-mm diameter, >10-mm length) was removed during sieving, dried, and weighed. Soil pH was estimated from a 1:1 soil/water mixture (Watson and Brown, 1998). Soil NO_3–N and NH_4–N were determined from 1:10 soil/2 mol L^{-1} KCl extracts using Cd reduction followed by a modified Griess–Ilosvay method and indophenol blue reaction (Mulvaney, 1996). Particulate organic matter (POM) was quantified using the method of Gregorich and Ellert (1993), where material retained on a 0.053-mm sieve was collected and analyzed for C content by dry combustion using a Carlo Erba NA 1500 CN analyzer (Thermo Scientific, Waltham, MA). Total soil C was also determined by dry combustion. As the pH was <7.2 for the depths sampled, total soil C was considered equivalent to SOC. Gravimetric data were converted to a volumetric basis for each sampling depth using field-measured soil bulk density (Blake and Hartge, 1986). All data were expressed on an oven-dry basis before statistical analysis.

Gas Flux Measurements: Protocol and Analysis

Fluxes of CO_2, CH_4, and N_2O were measured in the fallow phase of both treatments from 18 Oct. 2006 to 6 May 2008 using static chamber methodology as outlined by Hutchinson and Mosier (1981). Within each plot, gas samples were collected from duplicate two-part chambers, each consisting of a permanent polyvinyl chloride (PVC) pipe anchor (20.3-cm i.d.; 5.0-cm height) and a PVC cap (20.3-cm i.d.; 10.0-cm height) with a vent tube and sampling port. Anchors were placed in plots such that row and interrow management zones were included in the chamber. Gas samples from inside the chambers were collected with a 20-mL syringe at 0, 20, and 40 min after installation (approximately 1000 h each sampling day). After collection, gas samples were injected into 12-mL evacuated Exetainer glass vials sealed with butyl rubber septa (Labco Ltd., High Wycombe, UK). Measurement of gas fluxes was made approximately every week when near-surface soil depths were not frozen (48% of the fallow period). Otherwise, fluxes were measured every other week. During the course of the evaluation period, gas fluxes were measured 53 times.

Concentrations of CO_2, CH_4, and N_2O inside each vial were measured by gas chromatography 1 to 3 d after collection using a Shimadzu GC-17A gas chromatograph (Shimadzu Scientific Instruments, Kyoto, Japan) attached to an ISCO Retriever IV autosampler (Teledyne Isco, Lincoln, NE). Using this system, each sample was auto-injected and split into two sample loops, with 1 mL directed to a thermal conductivity detector (TCD) in series with a flame ionization detector (FID) using ultrapure He carrier gas. Ultrapure He and hydrocarbon-free air were used for combustion in the FID. The second sample loop directed 0.5 mL to a ^{63}Ni electron capture detector (ECD) with ultrapure N_2 as the carrier gas. Before reaching each detector, samples passed through a 4-m HayeSep D column (Hayes Separations, Bandera, TX) for the TCD and FID, and 2-m Porapak Q (Waters Corp., Milford, MA) and 4-m HayeSep D columns for the ECD. The gas chromatograph was calibrated with a commercial blend of CO_2 (350, 400, 1998.7 μL L^{-1}), CH_4 (1.00, 2.09, 10.1 μL L^{-1}), and N_2O (0.100, 0.401, 1.99 μL L^{-1}) balanced in N_2 from Scott Specialty Gases (Plumsteadville, PA). The gas flux was calculated from the change in concentration in the chamber headspace with time (Hutchinson and Mosier, 1981). Utilization of the algorithm by Hutchinson and Mosier (1981) provides a correction to the calculated flux rate should analyte concentration in the chamber headspace increase such that the diffusion gradient is altered, resulting in a curvilinear response for analyte concentration vs. time. Changes in analyte concentration during measurement periods of the study were predominantly small, however, resulting in calculated flux rates almost exclusively following a linear response.

To investigate potential temporal effects on gas flux during the fallow phase, the flux data were partitioned into five time periods based on the management of the rye cover crop: first winter (18 Oct. 2006–7 Mar. 2007), spring thaw until termination of rye (13 Mar. 2007–6 June 2007), termination of rye until soil freeze-up (19 June 2007–29 Nov. 2007), second winter (12 Dec. 2007–17 Mar. 2008), and spring thaw until planting (28 Mar. 2008–6 May 2008). Average flux rates of CO_2, CH_4, and N_2O were calculated within each time period, while cumulative flux across time periods was calculated by linearly interpolating data points and integrating the underlying area (Gilbert, 1987).

As a supplement to gas flux measurements, soil water content and temperature were measured when the soil was not frozen in 2007. Soil water content was measured in the surface 12 cm of soil using a time-domain reflectometry technique with a Campbell CS620 HydroSense System (Campbell Scientific, Logan, UT). Soil temperature was measured at a 6-cm depth with an Omega HH81A handheld digital thermometer attached to a heavy-duty T-type thermocouple probe (Omega Inc., Stamford, CT). Three measurements of soil water content and one measurement of soil temperature were made within 45 cm of the anchors during the 40-min gas sampling period. Values for soil water content were converted to water-filled pore space (WFPS) using field-measured soil bulk density for the surface 10 cm (Linn and Doran, 1984).

Statistical Analyses

Analysis of variance of soil and gas flux data was conducted using PROC mixed in SAS (Littell et al., 1996). The cropping system was considered a fixed effect, while replicate and replicate × cropping system were random effects. The P values for comparisons between cropping systems were computed for soil attributes and gas flux. The PDIFF option of the LSMEANS statement was used to document differences between means using a significance criterion of $P < 0.05$. For soil attributes, treatment means are representative across crop phases. Conversely, treatment means for gas flux are specific to the fallow phase of the associated cropping system.

RESULTS AND DISCUSSION

Mean daily air temperature during the evaluation period was 3.0°C (SD = 12.4°C), and varied 57°C between the minimum and maximum temperatures (−25.9 and 31.1°C, respectively) (Fig. 1a). The daily sum of solar radiation averaged 12.7 MJ m^{-2} d^{-1} (SD = 8.0 MJ m^{-2} d^{-1}), and rarely exceeded 30 MJ m^{-2} d^{-1} (Fig. 1b).

During the 19-mo fallow period, 111 d (~20%) received precipitation (Fig. 1c). Events with <10 mm of precipitation were predominant, occurring 88% of the time. During the evaluation, a total of 625 mm of precipitation was received at the study site, nearly equivalent to the long-term average of 627 mm for the same time period (NDAWN, 2008).

Fallow Effects on Near-Surface Soil Attributes

The cumulative effects of SW-S-F(rye) and SW-F on near-surface soil attributes were moderate. Soil bulk density, extractable N, identifiable plant material, and SOC did not differ between cropping systems at $P < 0.05$ (Table 1). Changes in soil attributes due to treatments within semiarid cropping systems are often slow to occur, owing to limited (and highly erratic) production of above- and belowground biomass with time (Mikha et al., 2006). Furthermore, the use of no-till management in both fallow treatments may have acted to buffer soil change, as cropping intensity effects on soil properties under no-till can be modest, particularly for soil bulk density and SOC (Benjamin et al., 2007; Sherrod et al., 2003). Among responsive soil attributes to the evaluated treatments, soil pH was lower under SW-S-F(rye) than SW-F at 5 to 10 cm, presumably due to greater acidification from subsurface-applied N (Bouman et al., 1995). Greater C inputs from roots and residue in SW-S-F(rye) contributed to increased POM-C relative to SW-F at 0 to 5 cm, as stover yield has been found to average 0.95 Mg ha^{-1} yr^{-1} more in SW-S-F(rye) than SW-F (Liebig et al., 2004). A similar trend for POM-C was observed between cropping systems at 5 to 10 cm ($P = 0.0680$), as well as for identifiable plant material at 0 to 5 cm ($P = 0.0571$). Biomass-associated soil C fractions often respond to treatment effects faster than SOC, making them valuable indicators of management trajectory in semiarid regions (Bowman et al., 1999; Sherrod et al., 2005). The fact that SOC did not differ between treatments implies greater heterotrophic respiration under SW-S-F(rye) than SW-F (Paul and Clark, 1996). A previous evaluation

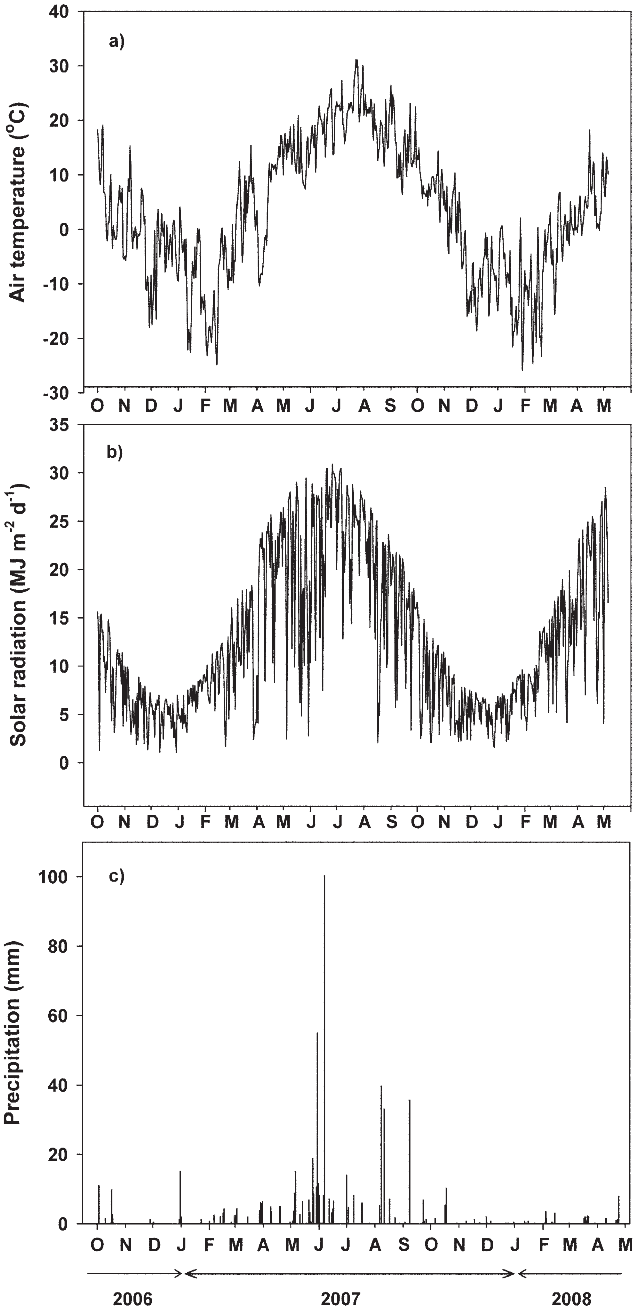

Fig. 1. (a) Air temperature, (b) solar radiation, and (c) precipitation at the field site from October 2006 through May 2008.

of the treatments supports this notion, as microbial biomass C in the surface 0 to 7.5 cm was found to be 101 kg C ha^{-1} greater in SW-S-F(rye) than SW-F (Liebig et al., 2004).

During the unfrozen period of 2007, the near-surface soil temperature increased and decreased linearly from the highest temperatures observed in late July (Fig. 2a). Soil temperature differed between treatments only once during this period, being greater under SW-F (21.3°C) than SW-S-F(rye) (19.3°C) on 7 Aug. 2007 ($P = 0.0289$; data not shown). Water-filled pore space rarely exceeded 60% during the unfrozen period of 2007, and averaged 45.3 and 45.6% for SW-F and SW-S-F(rye), respectively (Fig. 2b). At no time did WFPS differ between treatments during individual sampling dates (data not shown).

Table 1. Soil attributes for near-surface depths in spring wheat–chemical fallow (SW-F) and spring wheat–safflower–green fallow [SW-S-F(rye)] treatments before initiating gas flux measurements. Treatment means are representative across crop phases.

Soil depth	SW-S-F(rye)	SW-F	*P* value
cm			
	Soil bulk density, Mg m^{-3}		
0–5	1.08 (0.02)†	1.13 (0.03)	0.2244
5–10	1.41 (0.04)	1.42 (0.04)	0.8241
	Soil pH		
0–5	5.80 (0.07)	5.78 (0.08)	0.7716
5–10	5.66 (0.06)	5.94 (0.06)	0.0245
	Soil NO_3–N, kg N ha^{-1}		
0–5	6.2 (1.4)	2.8 (1.6)	0.0692
5–10	6.0 (1.3)	3.5 (1.4)	0.0763
	Soil NH_4–N, kg N ha^{-1}		
0–5	1.2 (0.5)	1.9 (0.4)	0.2243
5–10	1.7 (0.3)	1.3 (0.4)	0.3850
	Identifiable plant material, kg ha^{-1}		
0–5	760 (234)	229 (250)	0.0571
5–10	66 (46)	112 (57)	0.5389
	Soil organic C, Mg C ha^{-1}		
0–5	13.4 (0.5)	13.0 (0.5)	0.4486
5–10	13.8 (0.7)	14.1 (0.7)	0.5653
	Particulate organic matter C, kg C ha^{-1}		
0–5	1377 (177)	809 (205)	0.0302
5–10	484 (71)	263 (86)	0.0680

† Values in parentheses are standard errors of the mean.

Gas Flux Profiles

Carbon Dioxide

Flux of CO_2 from the soil is strongly influenced by biological processes, such as root respiration and decomposition. These processes, in turn, are affected by soil temperature, O_2 content, and water and substrate availability (Paul and Clark, 1996). Consequently, a variation in CO_2 flux is often a reflection of changes in abiotic conditions in the soil. While such a relationship is apparent (Buyanovsky et al., 1987), it is important to frame gas flux profiles from this evaluation in the context of weather-related variability, as it is often a defining attribute of agroecosystems in the northern Great Plains.

Carbon dioxide flux ranged from 1 mg CO_2–C m^{-2} h^{-1} (SW-F, 7 Mar. 2007) to 245 mg CO_2–C m^{-2} h^{-1} [SW-S-F(rye), 3 July 2007] during the fallow phase of both cropping systems (Fig. 3a). Most observations of CO_2 flux were <15 mg CO_2–C m^{-2} h^{-1} (62%), and occurred predominantly when the soil was frozen. Accordingly, emission of CO_2 was observed when the soil temperature was <0°C, consistent with other observations in semiarid cropping systems (Frank et al., 2006; Kessavalou et al., 1998). Conversely, CO_2 fluxes >15 mg CO_2–C m^{-2} h^{-1} were most prevalent between the months of May and September when respiration from roots and soil microorganisms was greatest. The coefficient of variability (CV) for CO_2 flux was relatively stable during the evaluation period, averaging 30% for duplicate chambers and 33% across replications (data not shown).

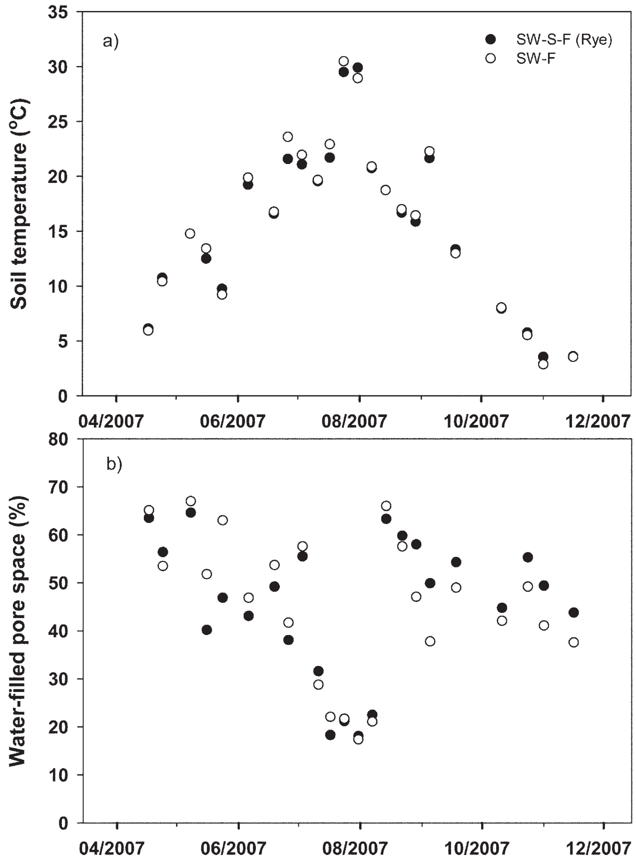

Fig. 2. (a) Soil temperature and (b) water-filled pore space for spring wheat–chemical fallow (SW-F) and spring wheat–safflower–rye (green fallow) [SW-S-F(rye)] treatments during the unfrozen period of 2007.

When the soil was not frozen in 2007, CO_2 flux closely followed trends in soil temperature (Fig. 2a). Although CO_2 flux during this period was more erratic than soil temperature, the variables were positively correlated at $P < 0.0001$ ($r = 0.42$; data not shown). Frank et al. (2006) found soil CO_2 efflux in continuous wheat and wheat–fallow cropping systems to be strongly affected by soil temperature, accounting for 62% of the variation in CO_2 flux during a 2-yr period. Flux of CO_2 during the 2007 unfrozen period was not associated with WFPS ($r = -0.07$, $P = 0.4600$) (Fig. 2b).

Methane

Methane flux was highly variable during the fallow phase of both cropping systems (Fig. 3b). Flux of CH_4 ranged from −19 μg CH_4–C m^{-2} h^{-1} (SW-F, 7 Aug. 2007) to 25 μg CH_4–C m^{-2} h^{-1} (SW-F, 12 Dec. 2007). The CV for CH_4 flux was substantial, averaging 154% for duplicate chambers and 186% across replications (data not shown). Uptake of atmospheric CH_4 was the dominant exchange process during the evaluation period, occurring 86% of the time. When expressed as a daily rate within fallow phases (Table 2), CH_4 uptake was generally lower than that observed by Kessavalou et al. (1998), who found CH_4 uptake to range from −1.3 to −12.3 g C ha^{-1} d^{-1} in wheat–fallow management systems in western Nebraska. Methane flux during the 2007 growing season was positively associated with WFPS ($r = 0.37$, $P < 0.0001$) (Fig. 2b), implying greater CH_4 uptake under drier soil conditions.

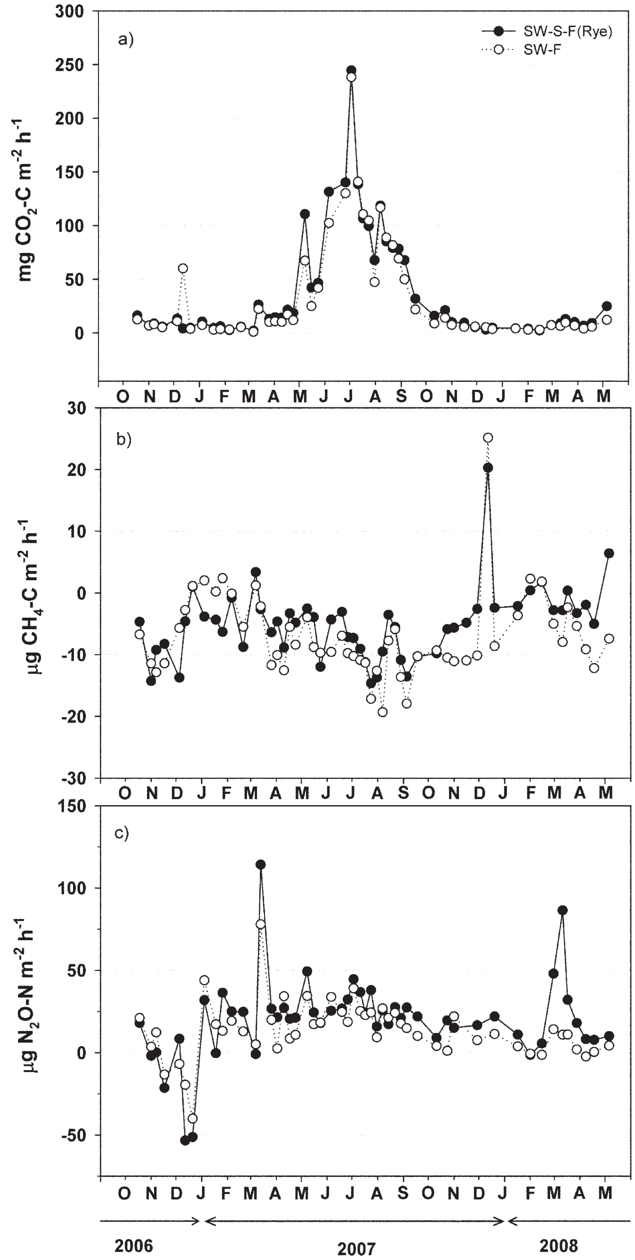

Fig. 3. (a) Flux of CO_2, (b) CH_4, and (c) N_2O for spring wheat–chemical fallow (SW-F) and spring wheat–safflower–green fallow [SW-S-F(rye)] treatments from October 2006 through May 2008.

Nitrous Oxide

Similar to CH_4, N_2O flux was highly variable, ranging from −53 to 114 μg N_2O-N m^{-2} h^{-1} during the 19-mo evaluation period (Fig. 3c). The CV for N_2O flux was greatest among all gases measured, averaging 160% for duplicate chambers and 192% across replications (data not shown). While most flux events fell within a range of 0 to 25 μg N_2O-N m^{-2} h^{-1} (65%), one uptake event and two emission events outside this range were prominent. Uptake of N_2O occurred in both cropping systems from 17 Nov. to 21 Dec. 2006, a period when the soil was dry and near-surface depths were beginning to freeze. Net uptake of

Table 2. Mean flux rates of CO_2, CH_4, and N_2O during five fallow phases of spring wheat–chemical fallow (SW-F) and spring wheat–safflower–green fallow [SW-S-F(rye)] treatments. Cumulative fluxes during the fallow period are also presented.

Treatment	First winter	Spring thaw to termination of rye	Termination of rye to soil freeze-up	Second winter	Spring thaw to planting	Cumulative flux
			CO_2–C, kg C ha^{-1} d^{-1}			Mg C ha^{-1}
SW-F	3.1	6.5	8.2	1.0	1.5	2.7
SW-S-F(rye)	2.0	14.5	9.8	1.3	2.3	3.7
P value	0.5468	0.0071	0.2916	0.2433	0.1034	0.1293
			CH_4–C, g C ha^{-1} d^{-1}†			kg C ha^{-1}
SW-F	−1.2	−2.4	−2.7	−0.3	−2.8	−1.0
SW-S-F(rye)	−2.2	−1.4	−1.5	−0.5	−0.5	−0.8
P value	0.2778	0.1495	0.0124	0.7232	0.0887	0.2629
			N_2O-N, g N ha^{-1} d^{-1}			kg N ha^{-1}
SW-F	4.1	5.7	3.0	1.3	−0.1	1.8
SW-S-F(rye)	−0.7	6.2	4.3	4.9	1.7	1.8
P value	0.1446	0.8553	0.3881	0.3750	0.4124	0.9979

† Negative flux implies net uptake.

N_2O, while rare, has been observed in cropping systems under a variety of climatic and edaphic conditions (Yamulki et al., 1995; Wagner-Riddle et al., 2007; Barton et al., 2008). Consumption of N_2O by soil is considered to occur through the conversion of N_2O to N_2 via denitrification (Blackmer and Bremner, 1976); however, nitrifiers have been reported to consume N_2O as well (Chapuis-Lardy et al., 2007). Associations of N_2O uptake with abiotic factors are lacking, as uptake has been observed under a variety of temperature, moisture, and substrate conditions (Chapuis-Lardy et al., 2007).

Two significant N_2O emission events occurred in mid-March 2007 and 2008 when the soils were thawing (Fig. 3c). Spring wheat–fallow and SW-S-F(rye) released 78 and 114 μg N_2O-N m^{-2} h^{-1}, respectively, on 13 Mar. 2007, while only SW-S-F(rye) had elevated N_2O emission on 11 Mar. 2008 (87 μg N_2O-N m^{-2} h^{-1}). Elevated levels of NO_3–N from residual fertilizer N combined with anaerobic conditions in near-surface depths probably contributed to the 2007 emission event. Conversely, N release from the decomposition of rye roots and residue in SW-S-F(rye) may have provided substrate for denitrification and subsequent N_2O emission not observed in SW-F in 2008. Compared with other evaluations, elevated N_2O emissions during spring thaw were greater than those observed in wheat–fallow cropping systems in central Montana (Dusenbury et al., 2008) and western Nebraska (Kessavalou et al., 1998), but were considerably lower than irrigated corn (*Zea mays* L.)-based cropping systems in northeast Colorado (Mosier et al., 2006).

Water-filled pore space during the 2007 growing season was not associated with N_2O flux ($r = -0.01$, $P = 0.9491$) (Fig. 2b), contrasting with other studies in wheat–fallow cropping systems (Barton et al., 2008; Kessavalou et al., 1998) as well as a nearby evaluation on mixed-grass prairie (Liebig et al., 2008) where positive correlations between WFPS and N_2O emission have been observed. A prevalence of aerobic soil conditions during the 2007 growing season probably contributed to the lack of association between WFPS and N_2O flux. Accordingly, N_2O released during this period was probably emitted via nitrification (Paul and Clark, 1996).

Fallow Phase Effects on Gas Flux

Compartmentalization of gas flux results into five phases based on management of the rye cover crop identified few differences between cropping systems. The flux of CO_2 was more than twice as great in SW-S-F(rye) than SW-F during the spring thaw to termination of rye phase (Table 2). The difference in CO_2 flux between cropping systems for this phase probably represents added CO_2 efflux from root respiration in SW-S-F(rye), as soil respiration would be the predominant source of CO_2 in SW-F (McGinn and Akinremi, 2001). The flux of CO_2 did not differ between cropping systems in the other four phases, although there was a trend toward greater CO_2 flux in SW-S-F(rye) than SW-F during the spring thaw following the second winter ($P = 0.1034$), presumably due to enhanced decomposition of rye roots and residue. Growing-season CO_2 flux from fallow in SW-F was comparable to other evaluations in the Great Plains, as Kessavalou et al. (1998) observed a CO_2 emission rate of 7.6 kg C ha^{-1} d^{-1} during fallow from wheat–fallow under no-till management in western Nebraska. During the evaluation period, fallow phases of SW-F and SW-S-F(rye) emitted 2.7 and 3.7 Mg CO_2–C ha^{-1}, respectively ($P = 0.1293$).

Methane flux during the five fallow phases was consistently negative, indicating uptake of CH_4 by both cropping systems. This finding is consistent with other evaluations in the Great Plains region, where dryland cropping systems have been found to be net sinks for atmospheric CH_4 (Liebig et al., 2005). Across the five fallow phases, CH_4 uptake was significantly greater in SW-F than SW-S-F(rye) following termination of the rye until soil freeze-up (Table 2). A similar trend between cropping systems was observed during spring thaw following the second winter ($P = 0.0887$). Repressed CH_4 uptake by SW-S-F(rye) during these two fallow phases may have been caused by excess NH_4–N in the soil solution from N fertilization and decomposition of rye roots, which would act to interfere with the activity of methanotrophic bacteria (Bronson and Mosier, 1994). Overall, SW-F and SW-S-F(rye) were minor sinks for CH_4 during their respective fallow phases, with cumulative uptake of −1.0 and −0.8 kg CH_4–C ha^{-1}, respectively ($P = 0.2629$).

No differences in N_2O flux were observed between cropping systems during any of the five fallow phases (Table 2). Furthermore, cumulative N_2O emission across the fallow phases for SW-F and SW-S-F(rye) was numerically the same (1.8 kg N ha^{-1}; $P = 0.9979$), and intermediate to other fallow-specific N_2O flux observations in northeastern Colorado (Mosier et al., 1991) and central Alberta (Lemke et al., 1999).

SUMMARY AND CONCLUSIONS

Assessing the effects of fallow on SOC and GHG flux is important to identify potential management interventions to reduce negative environmental impacts associated with dryland cropping systems. Given this context, this evaluation contrasted two cropping systems with a fallow component, chemical fallow (SW-F) and green fallow [SW-S-F(rye)], both under no-till management for 13 yr, for their effects on SOC and GHG flux. Results from this evaluation found no difference in SOC between cropping systems in near-surface depths, and few differences in soil attributes overall. It is probable that no-till management, with the accumulation of crop residues at the soil surface, masked crop sequence effects on soil attributes. Profiles of GHG flux in the fallow phases of SW-F and SW-S-F(rye) generally followed the expected trends; CO_2 emission was closely associated with air and soil temperature, CH_4 flux was highly erratic but mostly negative (implying net CH_4 uptake), and peak N_2O emission events occurred during spring thaw. Few differences in CO_2, CH_4, and N_2O fluxes between the fallow treatments were observed during a 19-mo period, however, indicating that there was no net GHG benefit from incorporating a rye cover crop during fallow.

It is possible that the use of unautomated chambers in this study resulted in poor coverage of episodic GHG events; events that are prevalent in semiarid agroecosystems (Barton et al., 2008). It is also possible that the time in treatment was too short for the cropping systems in question, and more time was needed to differentiate fallow effects on the response variables of interest. Furthermore, spatial variation across the study site (as reflected by large CVs) certainly contributed to the limited number of significant treatment effects. While these explanations may have merit in the context of this evaluation, future long-term studies of dryland cropping systems under no-till management should provide greater clarity regarding the role of crop intensification influences on the GHG balance during fallow. An important variable for future investigations includes the choice of cover crops (or cover crop mixtures) with respect to their effects on SOC and the emission of N_2O, two variables that largely dictate the GHG balance of no-till management systems (Six et al., 2004). Since establishing synchrony between plant N uptake and N supply is crucial to reducing N_2O emissions, a thorough understanding of cover crops effects on N balance (via fertilizer application, fixation, and mineralization) will be essential to these investigations.

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