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Net Global Warming Potential of Spring Wheat Cropping Systems in a Semiarid Region

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Abstract: Investigations of global warming potential (GWP) of semiarid cropping systems are needed to ascertain agriculture's contributions to climate regulation services. This study sought to determine net GWP for three semiarid cropping systems under no-tillage management in the northern Great Plains of North America: spring wheat (*Triticum aestivum* L.)—fallow (SW-F), continuous spring wheat (CSW) and spring wheat—safflower (*Carthamus tinctorius* L.)—rye (*Secale cereale* L.) (SW-S-R). Management records, coupled with published carbon dioxide (CO_2) emission estimates, were used to determine emissions from production inputs and field operations. Static chamber methodology was used to measure soil-atmosphere methane (CH_4) and nitrous oxide (N_2O) fluxes over a 3-year period and changes in profile soil organic carbon (SOC) stocks were determined over 18 years. Carbon dioxide emissions associated with production inputs and field operations were greatest for CSW, intermediate for SW-S-R and lowest for SW-F. All cropping systems were minor CH_4 sinks ($\leq$0.5 kg CH_4-C ha^{-1} yr^{-1}) and moderate N_2O sources (1.0 to 2.8 kg N_2O-N ha^{-1} yr^{-1}). No differences in SOC stocks were observed among cropping systems (P = 0.78), nor did SOC stocks change significantly from baseline conditions (P = 0.82). Summing across factors, net GWP was positive for SW-F and CSW, implying net greenhouse gas (GHG) emission to the atmosphere, while net GWP for SW-S-R was negative, implying net GHG uptake. Net GWP, however, did not differ among cropping systems (P = 0.17). Management practices that concurrently improve N use efficiency and increase SOC stocks are needed for semiarid cropping systems to be net GHG sinks.

Keywords: GRACEnet; Nitrous oxide; soil organic carbon

1. Introduction

Assessment of climate regulation services from cropping systems require detailed evaluations of field-level factors contributing to net global warming potential (GWP) [1]. Such evaluations include measurements of soil-atmosphere CH_4 and N_2O flux, soil organic carbon (SOC) stocks and greenhouse gas (GHG) emissions from field operations and production of inputs [2,3]. Due to their intensive measurement requirements, GWP estimates for cropping systems are limited [4]. The paucity of GWP estimates are particularly glaring in semiarid regions, where the nexus of human activities and anticipated climate change are projected to severely test the delivery of ecosystem services from agroecosystems in the future [5].

Previous evaluations of GWP in semiarid cropping systems reflect the influence of climatic and edaphic factors on biophysical attributes affecting GHG emissions and SOC stocks [2,6]. Nitrous oxide fluxes are highly episodic, responding to precipitation pulses and thaw events of frozen soil [7], whereas SOC stocks change slowly, frequently requiring a decade or longer for detection of treatment differences [8]. Accordingly, useful estimates of GWP in semiarid cropping systems couple intensive N_2O flux measurement campaigns [9] with long-term assessment of SOC stocks [10].

While climatic and edaphic influences on GWP are important, management practices employed by producers are the final determinants on GWP outcomes in semiarid cropping systems. Use of no-tillage has been found effective at reducing net GWP through accrual of SOC [11–13]. However, as inferred above, long-term adoption of no-tillage is critical to achieve GHG benefits. Nutrient management, particularly practices associated with synthetic N application, have found generally low N_2O fluxes in semiarid cropping systems (<7 g N_2O-N ha^{-1} d^{-1}) [14–16] but because of its high radiative forcing capacity (298 times more powerful than CO_2; Intergovernmental Panel on Climate Change (IPCC);) [17], fluxes of N_2O can comprise >50% of net GWP [14,18]. Though limited, investigations of crop rotation effects on GWP in semiarid regions have found monocultures to have greater net GWP compared to rotated crops [12,19].

Previous evaluations in semiarid regions have focused on determining individual management practice effects on GWP but few have considered cropping systems, where combined management (e.g., tillage, crop rotation, nutrient management, residue removal, etc.) is tested for its effect on GWP. A recent meta-analysis of 57 experiments showed combined management to be the most effective approach to reducing agroecosystem GWP [4], underscoring the value of field studies on this topic.

This report documents GWP outcomes from three cropping systems in a long-term experiment in the northern Great Plains of North America. The cropping systems, each under no-tillage management, differed in cropping intensity and diversity and were selected based on anticipated differences in GHG emissions and SOC stocks following a treatment framework developed by the Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet) [20]. This study extended previous evaluations in the region [21,22] by including gas flux measurements over the entire year, thereby potentially capturing mid-winter N_2O emission events which can account for a disproportionate share of annual flux [23]. Additionally, SOC stocks were inclusive of the soil profile, not just near-surface depths, thereby avoiding potentially misleading estimates of soil C storage under no-tillage [24].

Two hypotheses were postulated for the study: 1) semiarid cropping systems with greater crop diversity would result in lower net GWP and 2) if present, SOC accrual by cropping systems would be inadequate to offset N_2O flux and CO_2 emissions associated with input production and farm operations when expressed on a $CO_{2equiv.}$ basis.

2. Materials and Methods

2.1. Site Description

The experimental site was located approximately 6 km south of Mandan, North Dakota, USA (Latitude 46.771°, Longitude −100.949°, 591 m elevation) on the Area IV Soil Conservation Districts Cooperative Research Farm. The site is on gently rolling uplands (0–3% slope) with a silty loess mantle overlying Wisconsin age till. Predominant soil at the site is a Temvik-Wilton silt loam (Fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). Climate at the site is characterized as semiarid to sub-humid continental, with cold and dry winters, warm to hot summers and erratic precipitation [25]. From 1914 to 2012, annual precipitation averaged 414 mm, with over 75% of the total received from April through September. Average annual temperature is 4°C, though daily averages range from −11 °C in the winter to 21 °C in the summer.

2.2. Description of Cropping Systems

Treatments evaluated in the study were part of a long-term cropping system experiment established in 1994 [26]. Of the 12 treatment combinations included in the experiment, three were evaluated for this study: Spring wheat (*Triticum aestivum* L.)–fallow (SW-F; chemical fallow), continuous spring wheat with residue retained (Cont. SW) and spring wheat–safflower (*Carthamus tinctorius* L.)–fallow/rye (*Secale cereale* L.) (SW-S-R; green fallow). All crop sequences were managed using no-tillage, as soil was disturbed only at planting. Phases of each crop sequence were present every year and treatments were replicated three times. Individual plot size was 9.1 by 30.1 m.

Nutrient management of the treatments included spring fertilization of spring wheat and safflower and late-summer fertilization of rye during the evaluation period aligned with gas flux measurements (Oct 2006 through Oct 2009). For spring wheat and safflower, N fertilizer was applied concurrent with planting in amounts of 67 kg N ha^{-1} as urea after a crop and 34 kg N ha^{-1} after fallow. Supplemental N was applied to spring wheat and safflower in the form of monoammonium phosphate at a rate of 6 kg N ha^{-1} in 2008 and 2009. In 2007, 11 kg P ha^{-1} as triple superphosphate was applied to spring wheat and safflower at planting, whereas in 2008 and 2009 the same crops received 29 kg P ha^{-1} as monoammonium phosphate. No N or P was applied prior to the fallow phase in SW-F. Fertilization of rye included 6 kg N ha^{-1} and 29 kg P ha^{-1} as monoammonium phosphate during each year of the study.

All crops were planted in 19 cm rows with a John Deere Model 750 no-tillage drill (Deere & Company, Moline, IL, USA) at rates of 3.2 million viable seeds ha^{-1} for spring wheat and rye and 741,000 viable seeds ha^{-1} for safflower. Safflower was replanted in 2008 due to crop death from freezing conditions on 26 May. The rye phase was killed each year at anthesis with herbicide and left standing to trap and retain snow throughout the subsequent winter. Application of other pesticides for control of weeds and diseases followed typical practices used by area producers. Grain harvest was conducted at senescence using a John Deere Model 4420 combine with a straw chopper attachment and straight head. Detailed field operations over the course of the study are documented in Supplementary Materials (Supplementary Table S1).

2.3. Gas Flux Measurements

Fluxes of N_2O and CH_4 were measured in each phase of the three cropping systems from 18 October 2006 to 23 October 2009 using static chamber methodology [27]. 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 inter-row management zones were included in the chamber. Plot area covered by duplicate collars was 0.06 m^2. Gas samples from inside the chambers were collected with a 20 ml syringe at 0, 20 and 40 min after installation (approximately 10:00 each sampling day). The time zero sample was considered the field blank. After collection, gas samples were injected into 12 ml evacuated Exetainer glass vials sealed with butyl rubber septa (Labco Limited, Buckinghamshire, UK). Measurement of gas fluxes was made approximately every week when near-surface soil depths were not frozen. Otherwise, fluxes were measured every other week. Gas fluxes were measured 97 times over the evaluation period.

Concentration of N_2O and CH_4 inside each vial was measured by gas chromatography 1–3 d after collection using a Shimadzu GC-17A gas chromatograph (Shimadzu Scientific Instruments, Kyoto, Japan) attached to an ISCO Retriever IV autosampler (Teledyne Isco, Inc., Lincoln, NE, USA). 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 ultra-pure He carrier gas. Ultra-pure 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 ultra-pure N_2 as carrier gas. Prior to reaching each detector, samples passed through a 4-m HayeSep D column (Hayes Separations, Inc., Bandera, TX, USA) for the TCD and FID and 2-m Porapak Q (Waters Corp., Milford, MA, USA) and 4-m HayeSep D columns for the ECD. The gas chromatograph was calibrated with a commercial blend of N_2O (0.100, 0.401, 1.99 μL L^{-1}) and CH_4 (1.00, 2.09, 10.1 μL L^{-1}) balanced in N_2 from Scott Specialty Gases (Airgas USA LLC, Houston, TX, USA). Precision analysis expressed as coefficient of variation for 18 replicate injections of 0.401 μL N_2O L^{-1} and 2.09 μL CH_4 L^{-1} standards was 1.8 and 2.0%, respectively. Standard error associated with the precision analysis for each gas was ± 0.002 μL N_2O L^{-1} and ± 0.008 μL CH_4 L^{-1}. Gas flux was calculated from the change in concentration in the chamber headspace over time. If analyte concentration in the chamber headspace increased such that the diffusion gradient was altered, a correction to the calculated flux rate was applied resulting in a curvilinear response for analyte concentration versus time [27]. Calculated flux rates generally followed a linear response as changes in analyte concentration were small.

2.4. Supplementary Measurements

Near-surface soil water content and temperature were measured concurrently with gas flux when the soil was not frozen. Volumetric 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, Inc., Logan, UT, USA). Soil temperature was measured at a 6 cm depth with an Omega HH81A handheld digital thermometer attached to a T type thermocouple probe (Omega Engineering, Inc., Norwalk, CT, USA). Three measurements of soil water content and one measurement of soil temperature were made within 30 cm of each anchor during the second gas sampling period (t = 20 min). Values for volumetric water content were converted to water-filled pore space (WFPS) using field-measured soil bulk density for the surface 10 cm [28].

Precipitation, air temperature and solar radiation were monitored daily at a North Dakota Agricultural Weather Network (NDAWN) station within 2 km of the study. Relevant data were downloaded following each gas sampling event from the NDAWN website [29]. Precipitation received as snowfall was recorded from a National Oceanic Atmospheric Administration (NOAA) weather station 5 km north of the study [30].

2.5. Soil Carbon Determination

To capture long-term effects of management, soil organic C (SOC) was determined over an 18-yr period (1994–2012). Baseline soil samples were collected in 1993 prior to plot establishment in areas subsequently assigned to the SW-F cropping system treatment. Soil samples in 2012 were collected from each phase of all cropping system treatments prior to onset of spring field activities using equivalent protocols employed during collection of baseline samples. Samples were collected at three locations (east, middle and west) in each plot to a 1.22 m depth in increments of 0 to 0.076, 0.076 to 0.152, 0.152 to 0.305, 0.305 to 0.61, 0.61 to 0.914 and 0.914 to 1.22 m using a 3.3 cm (i.d.) Giddings hydraulic probe (Giddings Machine Co., Windsor, CO, USA). Collected samples were saved in double-lined plastic bags and placed in cold storage at 5 °C until processing.

Soil samples were dried at 35 °C for 3 to 4 d and ground by hand to pass a 2.0 mm sieve. Identifiable plant material (> 2.0 mm) was removed during sieving. Air-dry water content was determined for each sample using a 12 to 15 g subsample by measuring the difference in mass before and after drying at 105 °C for 24 h. Samples were analyzed for total soil C and N by dry combustion on soil ground to pass a 0.106 mm sieve [31]. Inorganic C was measured using the same fine-ground soil having a pH $\geq$ 7.2 by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with $FeCl_2$ [32]. Soil organic C was calculated as the difference between total C and inorganic C. Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density [33].

To eliminate effects of sampling depth and soil bulk density on SOC stocks, data from the 1993 and 2012 samplings were calculated on an equivalent mass basis assuming a soil profile mass of 18,885 Mg ha^{-1} (approximating the 0 to 1.22 m soil depth) for each cropping system treatment [34]. Additional detail on protocols and analyses associated with SOC determination may be found elsewhere [26].

2.6. Estimation of Global Warming Potential

Net GWP was calculated for each cropping system as the sum of emitted CO_2 equivalents from seven factors:

$$\text{Net GWP} = \text{SP} + \text{FP} + \text{PP} + \text{FO} + \Delta\text{SOC} + CH_4{}^{f} + N_2O^{f} \quad (1)$$

where SP, FP and PP addressed seed, fertilizer and pesticide and adjuvant production, respectively; FO addressed field operations, inclusive of seeding, pesticide application and harvest; ΔSOC was SOC change over an 18-yr period; $CH_4{}^{f}$ was soil-atmosphere CH_4 flux; and N_2O^{f} was soil-atmosphere N_2O flux. Emissions associated with seed production were assumed to be 0.13, 0.65 and 0.11 kg C kg^{-1} seed for spring wheat, safflower and rye, respectively [3]. Due to a lack of available estimates, seed production emissions for cotton (*Gossypium hirsutum* L.) and barley were assumed similar for safflower and rye. Production of fertilizer used conversions of 0.86 kg C kg^{-1} N and 0.17 kg C kg^{-1} P [3], while herbicide and insecticide emissions were calculated using conversions developed by West and Marland (2002) and Lal (2004) [3,35]. Emissions associated with adjuvants applied with herbicide were 0.27 kg C kg^{-1} oil [36]. Field operations emissions, inclusive of seeding, pesticide application and harvest, were determined using estimates by West and Marland (2002). Differences in SOC stocks between the 1993 and 2012 samplings were taken to represent net soil-atmosphere C exchange for each cropping system. Contributions of soil-atmosphere CH_4 and N_2O flux to GWP were based on annual flux rates using beginning and ending dates in mid-October.

For each factor contributing to GWP, C values were converted to CO_2 using a factor of 3.67 (44 g CO_2 mol^{-1} ÷ 12 g C mol^{-1}). For soil-atmosphere CH_4 and N_2O flux, CO_2 equivalents were calculated assuming direct GWP of 1 kg CH_4 ha^{-1} = 25 kg CO_2 ha^{-1} and 1 kg N_2O ha^{-1} = 298 kg CO_2 ha^{-1} (100-yr time horizon) [17]. Results for net GWP were expressed as kg $CO_{2\text{equiv.}}$ ha^{-1} yr^{-1}. To evaluate treatment effects on yield-scaled emissions, net GWP for each cropping system was divided by seed yield for spring wheat and safflower in kg ha^{-1}. Seed yields were annualized over rotation phases in SW-F and SW-S-R to align with values calculated for net GWP.

2.7. Data Analyses

Gas flux data were tested for normality using skewness, kurtosis and Kolmogorov-Smirnov coefficients before and after data were log-transformed. Data transformation did not improve normality of the data, so original gas flux data were used for statistical analyses. A mixed repeated measures model was used to analyze the effects of year, quarterly period (1 December–28/29 February, 1 March–31 May, 1 June–31 August and 1 September–30 November), crop phases (spring wheat, safflower, rye and fallow) and cropping system on hourly rates of soil-atmosphere N_2O and CH_4 flux. A time series covariance structure was used in the repeated measures model, where correlations decline over time [15]. Cumulative fluxes of N_2O and CH_4 were calculated by linearly interpolating data points and integrating the underlying area prior to summing values [37].

Variables associated with GWP, along with grain yield and cumulative soil-atmosphere CH_4 and N_2O flux, were analyzed using PROC GLIMMIX in SAS [38] with cropping systems and replicates as fixed and random effects, respectively. The slice option in the LSMEANS statement was used to generate P-values for comparisons. Differences among means were documented using a significance criterion of $P \leq 0.05$. Standard error of the mean was used as a measure of dispersion. Where applicable, associations between measured parameters were identified using Pearson correlation analysis.

3. Results

3.1. Weather Conditions and Soil Attributes

3.1.1. Precipitation, Air Temperature and Solar Radiation

Weather conditions during the 3-yr period of gas flux measurements were wetter and warmer than normal. Cumulative precipitation was 1652 mm, approximately 410 mm greater than the long-term mean [29]. No precipitation was recorded on 858 days (77%) (Figure 1A). Of the 244 days where precipitation was recorded, minor (<5 mm), moderate (5–25 mm) and major (>25 mm) events occurred on 150, 80 and 14 days, respectively. Notable extreme events (≥100 mm within 24 h) occurred on 7 June 2007 and 15 June 2009 (Figure 1A). Snow cover was present January–April and December in 2007, February, March, November and December in 2008 and January–April in 2009.

Mean daily air temperature during the study was 5.4 ± 0.4 °C, approximately 1.4 °C warmer than the long-term mean [29]. Despite this, 35% of the study period had a recorded daily air temperature <0 °C (391 d) (Figure 1B). Typical fluctuations in mean daily air temperature were observed over the course of the study, ranging from −28.3 °C (15 January 2009) to 31.1 °C (23 July 2007). Daily sums of solar radiation averaged 14.4 ± 0.3 MJ m^{-2} d^{-1}. Instances of solar radiation values exceeding 30 MJ m^{-2} d^{-1} increased each year of the study, occurring 5, 8 and 13 times in the summer months of 2007, 2008 and 2009, respectively (Figure 1C).

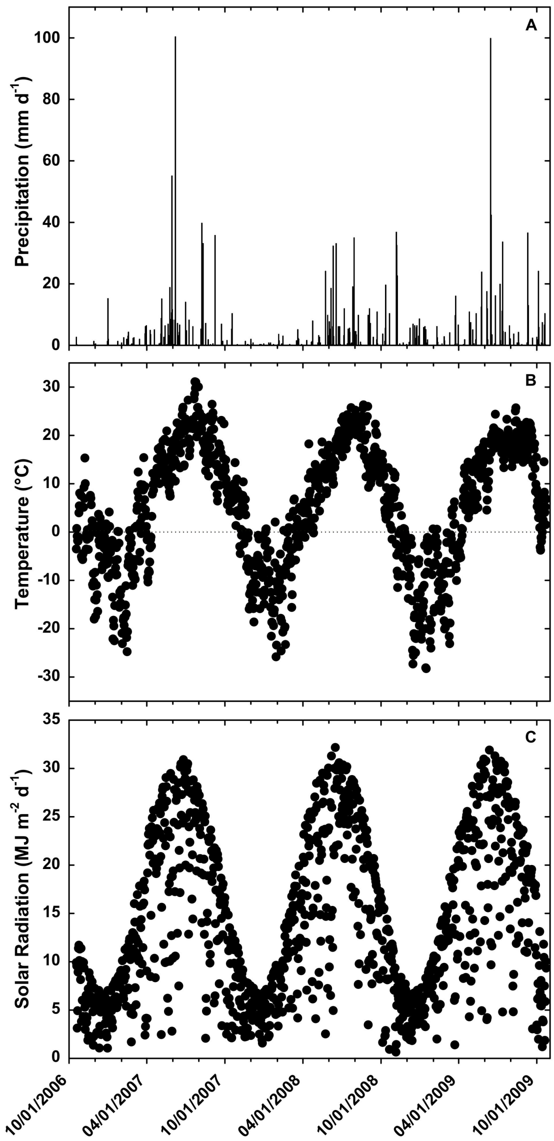

Figure 1. Daily precipitation (**A**), daily mean air temperature (**B**) and daily total solar radiation (**C**) 2 km from study site from 18 October 2006 through 23 October 2009.

3.1.2. Soil Temperature and Water-Filled Pore Space

Near-surface soil temperature averaged 15.7 ± 0.5 °C and ranged from 0.8 to 33.7 °C when the soil was not frozen (Figure 2A). Soil temperature was greatest during the first growing season (17.4 ± 0.8 °C), intermediate in the third (15.7 ± 0.7 °C) and least in the second (14.0 ± 0.9 °C), with soil temperature in the first and second years being significantly different ($P = 0.01$). Soil temperature did not differ among cropping systems, with mean values of 15.9 ± 0.9 °C for SW-F, 15.5 ± 0.8 °C for CSW and 15.7 ± 0.8 °C for SW-S-R ($P = 0.95$).

Water-filled pore space averaged 42.2 ± 1.0% and ranged from 12.3 to 76.4% when the soil was not frozen (Figure 2B). Aerobic soil conditions were prevalent throughout the study period, as 90% of the 174 WFPS observations were ≤60%. Similar to soil temperature, WFPS differed among years, with soil conditions significantly drier in the first year (38.6 ± 1.8%) compared to the third (46.2 ± 2.0%) and the second year not different from both (42.3 ± 1.3%) ($P \leq 0.01$). Water-filled pore space did not differ among cropping systems, with mean values of 43.4 ± 1.7% for SW-F, 43.0 ± 1.9% for CSW and 40.3 ± 1.6% for SW-S-R ($P = 0.39$). Water-filled pore space was negatively associated with soil temperature ($r = -0.29$; $P = 0.03$).

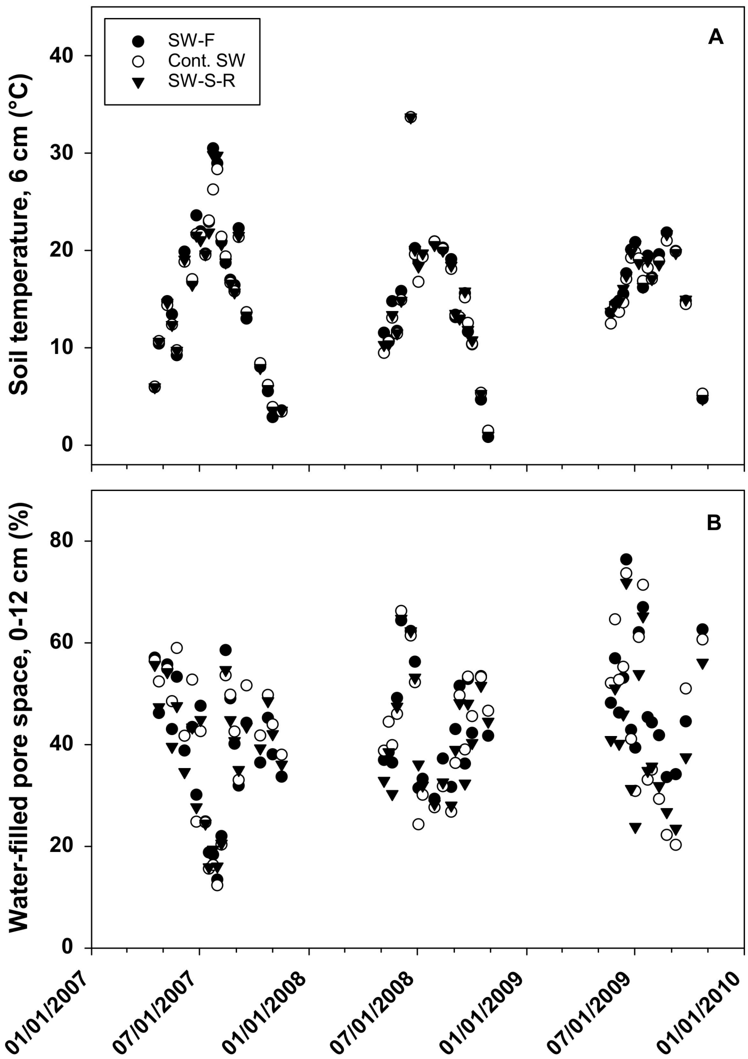

Figure 2. Near-surface soil temperature (**A**) and water-filled pore space (**B**) within spring wheat–fallow (SW-F), continuous spring wheat (Cont. SW) and spring wheat–safflower–rye (SW-S-R) cropping systems during unfrozen periods from April 2007 through October 2009. Mean values are reported across crop phases for SW-F and SW-S-R.

3.2. Crop Yield

Mean values of spring wheat grain yield did not differ among treatments over the three-year study (Table 1). In 2009, however, grain yield was greater in SW-S-R (3.37 Mg ha^{-1}) compared to CSW and SW-F (Mean = 2.53 Mg ha^{-1}) ($P \leq 0.01$). Greater retention of overwinter precipitation by SW-S-R, coupled with lower water-use efficiencies of CSW and SW-F, may have contributed to spring wheat grain yield differences among cropping systems in 2009 [39]. Safflower grain and rye biomass yields in SW-S-R averaged 1.28 and 3.75 Mg ha^{-1}, respectively (Table 1).

Table 1. Crop yields for cropping systems evaluated in study, 2007–2009.

Spring Wheat	**Grain yield (Mg ha^{-1})**			
	2007	**2008**	**2009**	**Mean**
Spring wheat–Fallow	2.94 (0.02) †	3.11 (0.10)	2.47 (0.11) b ‡	2.84 (0.10)
Continuous spring wheat	2.57 (0.03)	2.68 (0.16)	2.58 (0.03) b	2.61 (0.05)
Spring wheat–Safflower–Rye	2.71 (0.16)	3.08 (0.14)	3.37 (0.02) a	3.05 (0.11)
P-value	*0.11* ¶	*0.06*	*<0.01*	*0.07*
Safflower	**Grain yield (Mg ha^{-1})**			
	2007	**2008**	**2009**	**Mean**
Spring wheat–Safflower–Rye	1.36 (0.03)	1.17 (0.23)	1.30 (0.13)	1.28 (0.08)
Rye	**Biomass yield (Mg ha^{-1})**			
	2007	**2008**	**2009**	**Mean**
Spring wheat–Safflower–Rye	5.19 (0.61)	3.78 (0.28)	2.30 (0.75)	3.75 (0.51)

† Values in parentheses reflect the standard error of the mean. ‡ Means in a column with unlike letters differ ($P \leq 0.05$). ¶ *P*-values represent comparison of spring wheat grain yield among cropping systems.

3.3. Factors Contributing to GWP

3.3.1. Input Production and Field Operations

Differences in cropping intensity and diversity among treatments were expressed through estimated CO_2 emissions associated with production inputs and field operations (Tables 2 and 3). Carbon dioxide emissions associated with seed production were reduced by at least half in SW-F compared to CSW and SW-S-R due to the lack of seeding during the chemical fallow phase in the former (Table 3). Estimated CO_2 emissions from the production of N and P fertilizer differed across treatments (Table 3), with values greatest in CSW (238 kg $CO_{2\,equiv.}$ ha^{-1}), intermediate in SW-S-R (171 kg $CO_{2\,equiv.}$ ha^{-1}) and least in SW-F (66 kg $CO_{2\,equiv.}$ ha^{-1}). Here, fertilizer-associated emissions were reflected through both cropping system diversity and intensity. Diversity effects were expressed through the lower fertilization requirement during the rye 'green fallow' phase in SW-S-R compared to continuous monoculture cropping (CSW), whereas intensity effects were tied to fertilization in alternate years at a reduced application rate in SW-F compared to both continuously cropped treatments (Table 2). Carbon dioxide emissions associated with pesticide production did not differ among treatments (Table 3). The absence of a treatment effect on pesticide-associated CO_2 emissions was driven by intensive chemical weed control during the fallow phase of SW-F and pre-plant herbicide applications in the safflower phase of SW-S-R, both of which served to elevate estimated CO_2 emissions relative to CSW (Table 2). Carbon dioxide emissions associated with field operations were greatest in CSW (143 kg $CO_{2\,equiv.}$ ha^{-1}), intermediate in SW-S-R (128 kg $CO_{2\,equiv.}$ ha^{-1}) and least in SW-F (93 kg $CO_{2\,equiv.}$ ha^{-1}) (Table 3). The frequency of grain harvest was the primary factor contributing to treatment differences, as estimated CO_2 emissions from mechanical harvest accounted for 32–50% of total field operations emissions (data not shown).

Table 2. Carbon dioxide emissions associated with production inputs and field operations for cropping systems evaluated in study. Values derived from Lal (2004), Özilgen and Sorgüven (2011) and West and Marland (2002).

Crop rotation	Phase	Year	Seed Production	Fertilizer Production	Pesticide Production	Field Operations
				kg $CO_{2\ equiv.}$ ha^{-1}		
Spring wheat–Fallow	Spring wheat	2007	43	112	104	152
		2008	42	143	50	134
		2009	43	143	83	143
	Fallow	2007	0	0	124	37
		2008	0	0	153	47
		2009	0	0	160	47
Continuous spring wheat	Spring wheat	2007	43	218	114	152
		2008	42	248	50	134
		2009	43	248	83	143
Spring wheat–Safflower–Rye	Spring wheat	2007	43	218	114	152
		2008	42	248	50	134
		2009	43	248	83	143
	Safflower	2007	46	218	330	171
		2008	92 †	248	72	168
		2009	46	248	110	152
	Rye	2006/2007 ‡	38	37	7	83
		2007/2008	38	37	34	64
		2008/2009	38	37	96	83

† Safflower planted twice in 2008. ‡ Rye cover crop planted in fall and killed at anthesis in the following year.

Table 3. Cropping system effects on net global warming potential (GWP), yield-scaled GWP and contributing factors.

Factor	Spring Wheat–Fallow	Continuous Spring Wheat	Spring Wheat–Safflower–Rye
		(kg $CO_{2equiv.}$ ha^{-1} yr^{-1})	
Seed production	21 b †	42 a	47 a
Fertilizer production	66 c	238 a	171 b
Pesticide production	112	82	99
Field operations ‡	93 c	143 a	128 b
SOC change	69	−205	−1244
CH_4 flux	−19 ¶	−11	−14
N_2O flux	479	1658	799
Net GWP	822	1948	−14
		(kg $CO_{2equiv.}$ kg^{-1} grain)	
Yield-scaled GWP	0.59	0.75	−0.01

† Means in a row with unlike letters differ ($P \leq 0.05$). ‡ Inclusive of emissions associated with seeding, pesticide application and harvest. ¶ Negative values imply net CO_2 uptake.

3.3.2. Soil Organic Carbon

Soil organic carbon values assimilated stocks across an approximate 1.22 m depth using an equivalent mass calculation method. Accordingly, SOC stocks encompassed the rooting profile for crops included in the study [40]. Mean SOC stocks were 195.6 ± 6.8 Mg C ha^{-1} in 1993 prior to treatment deployment (Figure 3). Eighteen years later mean SOC stocks were 198.0 ± 4.6 Mg C ha^{-1} and did not differ from baseline stocks (P = 0.82). Moreover, SOC stocks in 2012 did not differ among cropping systems (P = 0.78), with mean values of 195.4 ± 10.3, 196.7 ± 3.5 and 201.8 ± 10.9 Mg C ha^{-1} for SW-F, CSW and SW-S-R, respectively (Figure 3). Substantial variation in SOC stocks were observed across replications, ranging from 175.1 to 208.2 Mg C ha^{-1} in SW-F, 193.0 to 203.8 Mg C ha^{-1} in

CSW and 187.1 to 223.2 Mg C ha^{-1} in SW-S-R. No differences in inorganic C were observed among treatments in 2012 (data not shown).

Change in SOC stocks over the 18-yr measurement period did not differ among treatments ($P = 0.87$). Numerical outcomes suggested CSW and SW-S-R were minor and moderate C sinks (0.06 and 0.34 Mg C ha^{-1} yr^{-1} accrual, respectively), while SW-F was a minor C source (0.02 Mg C ha^{-1} yr^{-1} loss). However, inferences of soil C sink/source capacity for each treatment were tenuous given the high variability of measured values in 2012.

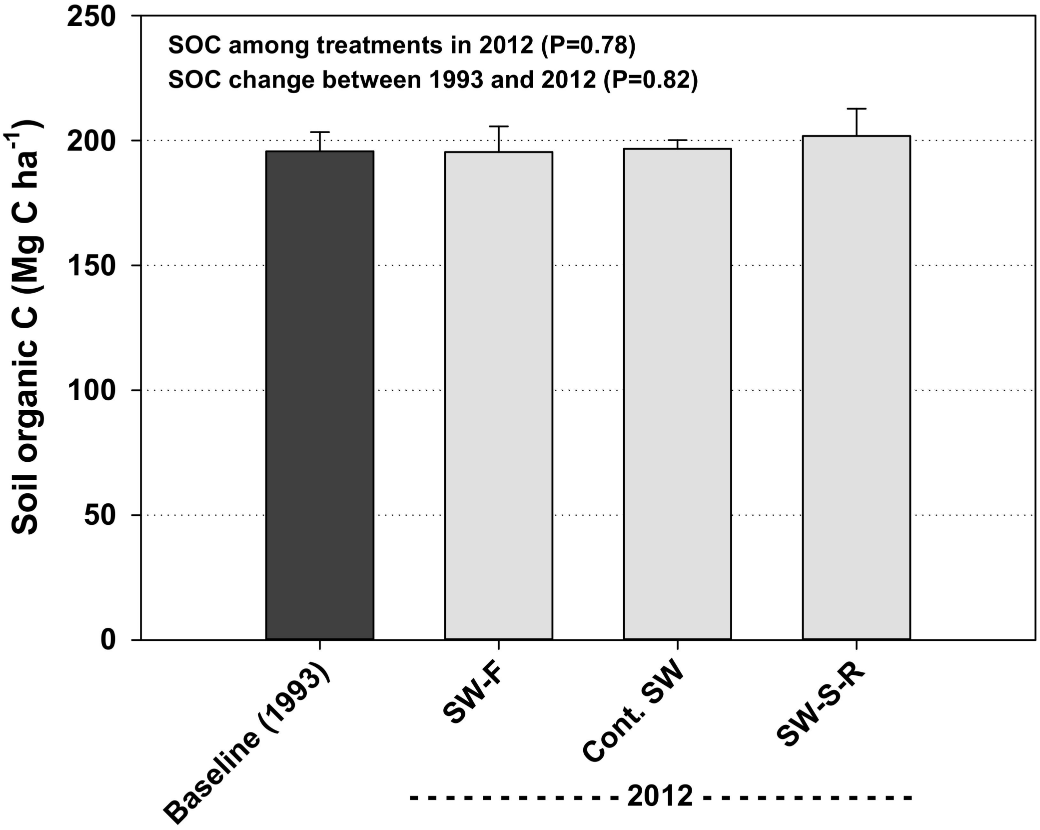

Figure 3. Soil organic carbon stocks in cropping system treatments in 1993 and 2012 using an equivalent soil mass of 18,885 Mg ha^{-1}. Soil depth to reach equivalent mass was 1.37 m in 1993 and 1.27, 1.27 and 1.28 m in 2012 for spring wheat–fallow (SW-F), continuous spring wheat (Cont. SW) and spring wheat–safflower–rye (SW-S-R) cropping systems, respectively.

3.3.3. CH_4 Flux

Methane uptake was the dominant exchange process throughout the evaluation period, occurring 77% of the time. Ranges in hourly CH_4 flux rates were consistent across treatments, with minimum and maximum values of −20 to 25 μg CH_4-C m^{-2} h^{-1} for SW-F, −20 to 26 μg CH_4-C m^{-2} h^{-1} for CSW and −18 to 26 μg CH_4-C m^{-2} h^{-1} for SW-S-R (Figure 4). Methane flux was positively associated with WFPS when the soil was not frozen ($r = 0.63$; $P \leq 0.01$), implying drier soil conditions favored CH_4 uptake. Conversely, CH_4 flux was negatively associated with near-surface soil temperature ($r = -0.22$; $P \leq 0.01$).

Hourly CH_4 flux rates differed among years, seasons, crop phases and cropping systems (Table 4). Uptake of CH_4 was greater during the first evaluation year compared to years 2 and 3, presumably due to drier and warmer near-surface soil conditions in the former (Figure 2). Mean hourly CH_4 uptake rates were greatest in summer and fall (−7.2 and −8.3 μg CH_4-C m^{-2} h^{-1}, respectively), intermediate in spring (−4.3 μg CH_4-C m^{-2} h^{-1}) and least in winter (−0.1 μg CH_4-C m^{-2} h^{-1}). Among crop phases, mean hourly CH_4 uptake differed between rye (−3.6 μg CH_4-C m^{-2} h^{-1}) and the other crop phases (Range = −5.5 to −6.0 µg CH_4-C m^{-2} h^{-1}). Methane uptake rates were lower in CSW and SW-S-R (−4.0 and −4.9 µg CH_4-C m^{-2} h^{-1}, respectively) compared to SW-F (−6.7 µg CH_4-C m^{-2} h^{-1}). Similarly, cumulative CH_4 uptake over the course of the study was −1.6 ± 0.4, −0.9 ± 0.1 and −1.2 ± 0.1 kg CH_4-C ha^{-1} for SW-F, CSW and SW-S-R (Figure 5A), equating to annual CH_4 uptake rates of −0.5, −0.3 and −0.4 kg CH_4-C ha^{-1} yr^{-1}, respectively.

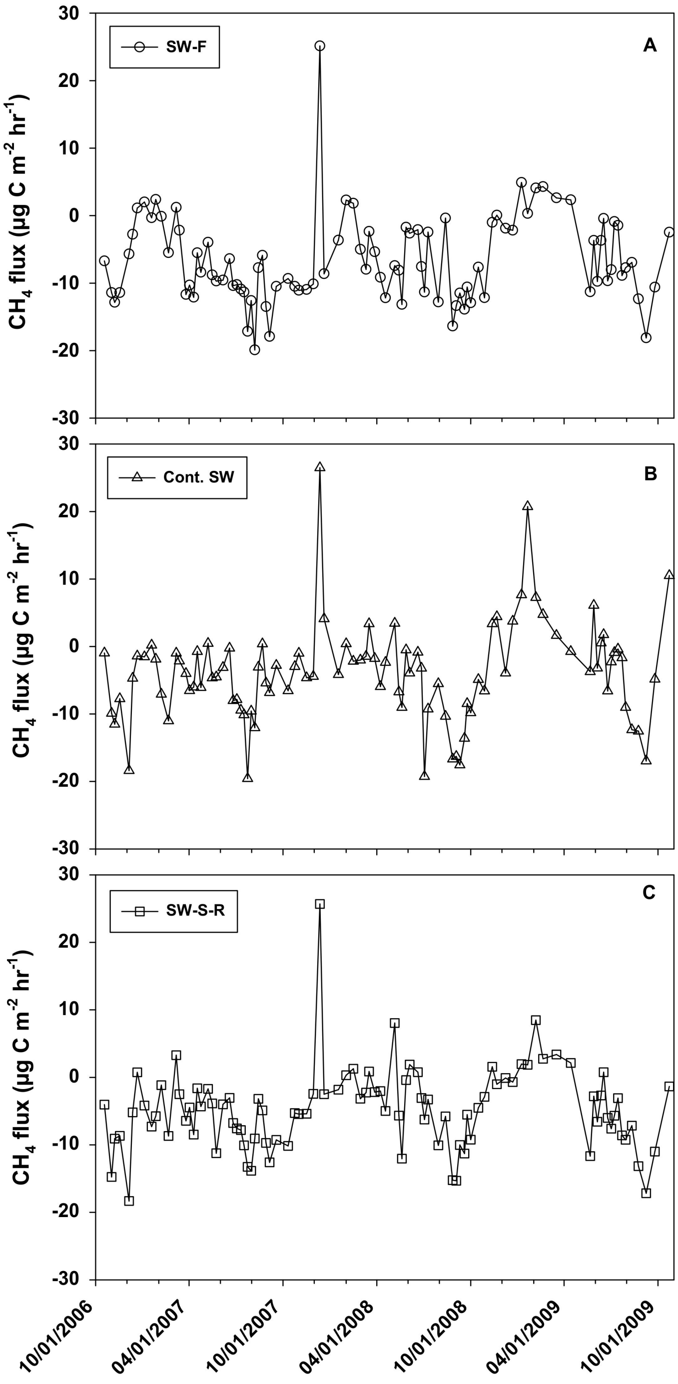

Figure 4. Methane flux for spring wheat–fallow (SW-F; (**A**)), continuous spring wheat (Cont. SW; (**B**)) and spring wheat–safflower–rye (SW-S-R; (**C**)) cropping systems from 18 October 2006 through 23 October 2009. Mean values are reported across crop phases for SW-F and SW-S-R.

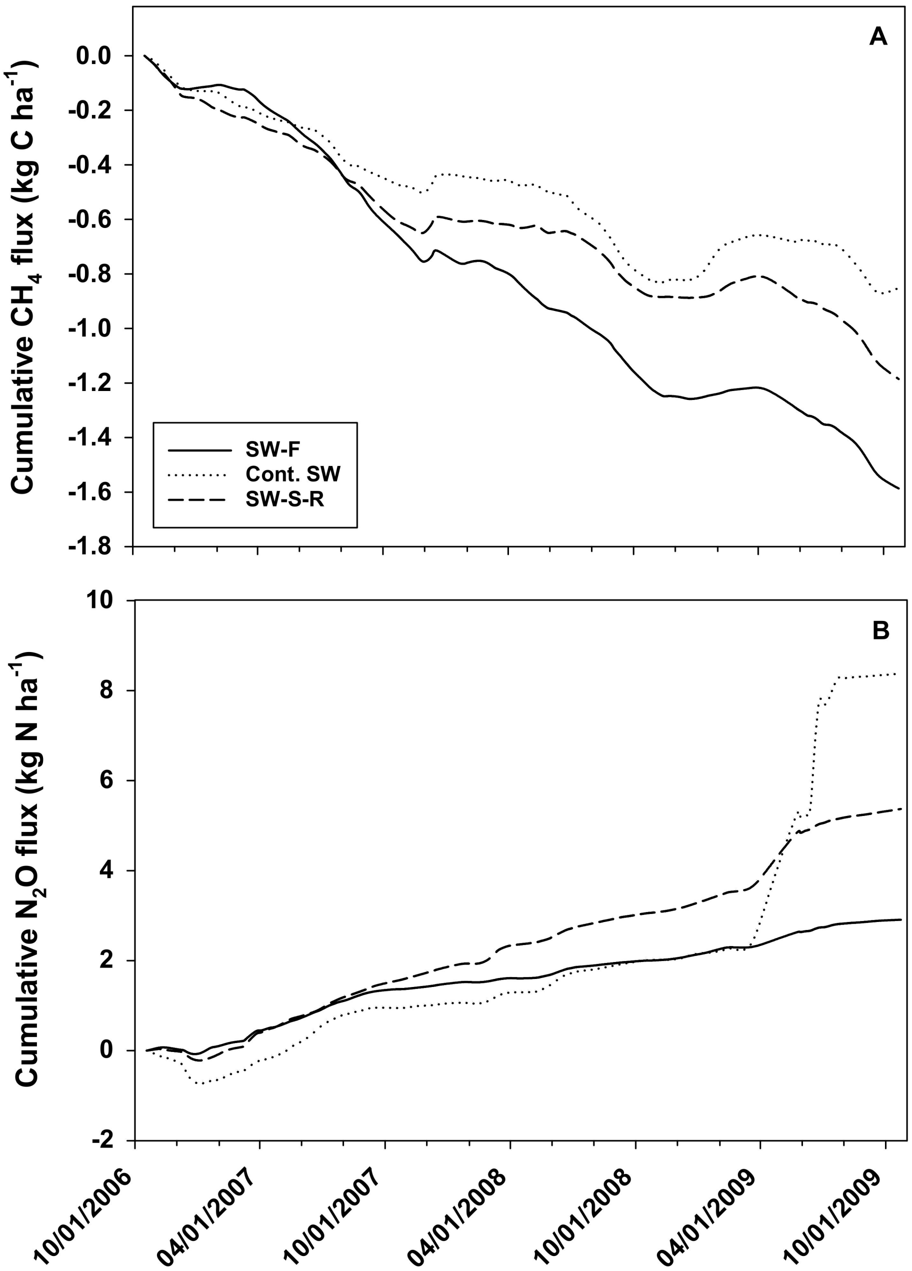

Figure 5. Cumulative flux of CH_4 (**A**) and N_2O (**B**) for spring wheat–fallow (SW-F), continuous spring wheat (Cont. SW) and spring wheat–safflower–rye (SW-S-R) cropping systems from 18 October 2006 through 23 October 2009.

3.3.4. N_2O Flux

Net emission of N_2O to the atmosphere was dominant during the evaluation period, occurring 91% of the time. Though limited, N_2O consumption was more common under CSW (14%) than under SW-F (9%) and SW-S-R (5%) and was especially prevalent in November and December of 2006 (Figure 6). Hourly N_2O flux rates were most variable in CSW, ranging from −123 to 1491 μg N_2O-N m^{-2} h^{-1}. Conversely, variation in N_2O flux rates for the other cropping systems was moderate, ranging from −40 to 78 μg N_2O-N m^{-2} h^{-1} for SW-F and −52 to 191 μg N_2O-N m^{-2} h^{-1} for SW-S-R (Figure 6). Notable 'hot moments' for N_2O flux aligned with late-winter snowmelt (13 March 2007; 11 March 2008; 14 April 2009) or after significant rainfall (17 June 2009; 15 July 2009). Nitrous oxide flux was positively associated with WFPS (r = 0.22; P ≤0.01) but was not associated with near-surface soil temperature (r = 0.05; P = 0.56).

Table 4. Mean hourly flux for CH_4 and N_2O partitioned by year, quarterly periods, crop phase and cropping systems. P values for comparisons within an effect are provided below the listed means.

Effect	CH_4 Flux (μg CH_4-C m^{-2} h^{-1})	N_2O Flux (μg N_2O-N m^{-2} h^{-1})
Year †		
1	−7.0 (0.3) a ‡,¶	17.2 (1.5) b
2	−4.8 (0.5) b	14.0 (0.9) b
3	−3.6 (0.4) b	29.9 (7.6) a
P value	*<0.01*	*0.01*
Season		
December–February	−0.1 (0.7) c	8.3 (2.2) b
March–May	−4.3 (0.4) b	27.0 (3.2) a
June–August	−7.2 (0.3) a	29.9 (6.0) a
September–November	−8.3 (0.4) a	7.1 (1.0) b
P value	*<0.01*	*<0.01*
Crop phase		
Spring wheat	−5.5 (0.3) a	24.0 (4.2)
Safflower	−6.0 (0.7) a	19.4 (1.9)
Rye	−3.6 (0.5) b	17.9 (2.0)
Fallow	−6.0 (0.6) a	8.6 (1.5)
P value	*<0.01*	*0.80*
Cropping system		
Spring wheat–Fallow	−6.7 (0.4) a	12.1 (1.1)
Continuous spring wheat	−4.0 (0.6) b	35.8 (12.4)
Spring wheat–Safflower–Rye	−4.9 (0.3) b	19.3 (1.2)
P value	*0.01*	*0.06*

† Values for year effect determined using beginning and ending dates in mid-October. ‡ Values in parentheses reflect the standard error of the mean. ¶ Means in a column with unlike letters differ ($P \leq 0.05$).

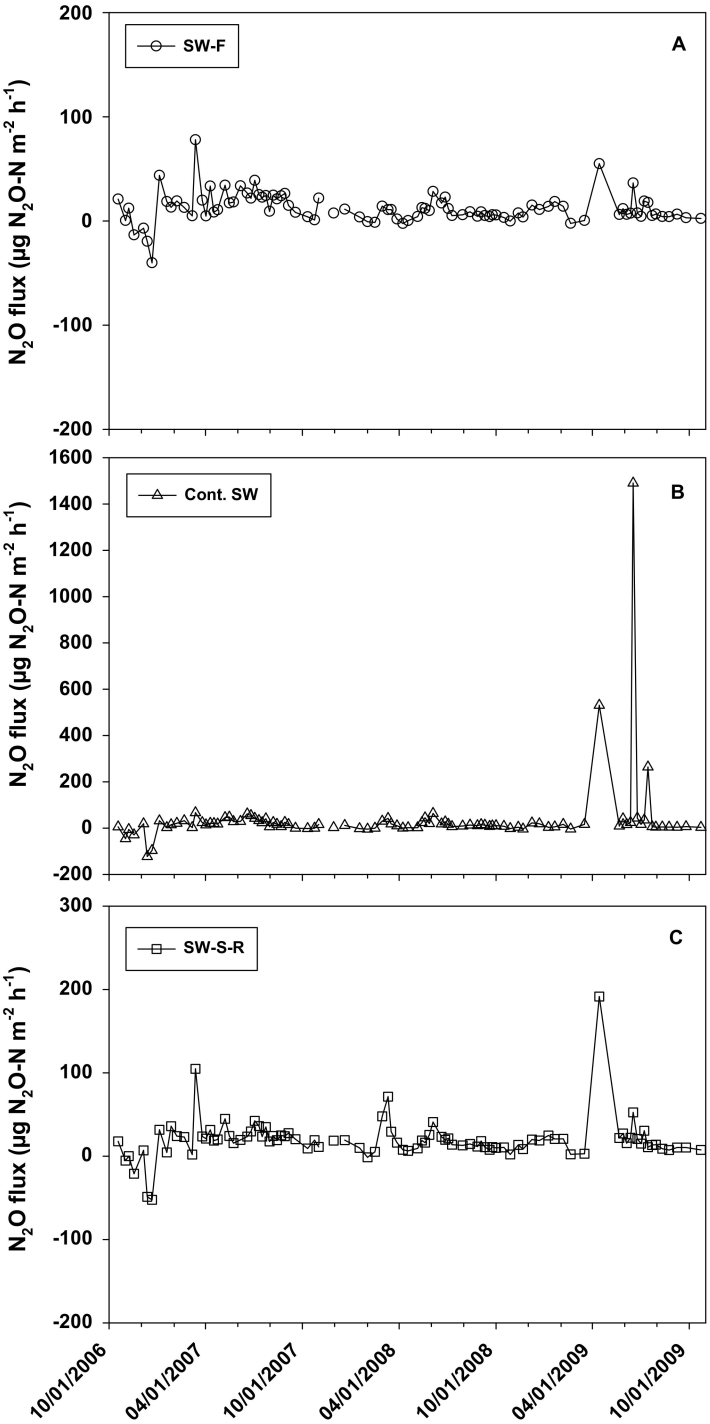

Figure 6. Nitrous oxide flux for spring wheat–fallow (SW-F; (**A**)), continuous spring wheat (Cont. SW; (**B**)) and spring wheat–safflower–rye (SW-S-R; (**C**)) cropping systems from 18 October 2006 through 23 October 2009. Mean values are reported across crop phases for SW-F and SW-S-R.

Year and season affected hourly N_2O flux rates (Table 4). Emission of N_2O was greater in the third year compared to years 1 and 2, a result likely facilitated by wetter soil conditions in the former (Figure 2). Nitrous oxide emission was greater in spring and summer (29.0 and 29.9 µg N_2O-N m^{-2} h^{-1}, respectively) compared to fall and winter (7.1 and 8.3 µg N_2O-N m^{-2} h^{-1}, respectively). Mean hourly N_2O flux did not differ among crop phases and cropping systems despite large numerical differences within phases and systems. Evaluation of plot-scale data found a large proportion of positive N_2O fluxes occurred in the third replication of the study, where inherent edaphic features contributed to increased water retention (data not shown). Cumulative N_2O emission over the study period was 2.9 ± 0.5, 8.4 ± 3.5 and 5.4 ± 0.5 kg N_2O-N ha^{-1} for SW-F, CSW and SW-S-R (Figure 5B), equating to annual N_2O emission rates of 1.0, 2.8 and 1.8 kg N_2O-N ha^{-1} yr^{-1}, respectively. Emission of N_2O as a percentage of N fertilizer applied was high, averaging 5.1, 3.9 and 3.6% for SW-F, CSW and SW-S-R, respectively.

3.4. Net GWP and GHGI

Factors contributing to net GWP across cropping systems decreased in relative impact in the order of soil-atmosphere N_2O flux (1), SOC change (2), CO_2 emissions associated with fertilizer production (3), field operations (4), pesticide production (5) and seed production (6) and soil-atmosphere CH_4 flux (7) (Table 3). Of notable exception to the mean factor rankings within cropping systems was CO_2 emissions associated with pesticide production, which had the second largest impact on net GWP in SW-F after soil-atmosphere N_2O flux. Individual factors differing among cropping systems included CO_2 emissions associated with seed and fertilizer production and field operations (reviewed above), whereas all other factors did not differ among systems owing to 1) similar pesticide application requirements and 2) high variation in SOC change and soil-atmosphere N_2O flux. Soil-atmosphere N_2O flux comprised the majority of emissions in SW-F and CSW, accounting for 58 and 85% of net GWP, respectively. For the two cropping systems where SOC accrual was observed (CSW and SW-S-R), only SW-S-R was able to offset N_2O emissions with soil C sequestration. Nitrous oxide emission accounted for 64% of the soil C sink capacity in SW-S-R when expressed on a $CO_{2equiv.}$ basis, while SOC change negated 12% of observed N_2O emission in CSW.

Summing across factors, net GWP was positive for SW-F and CSW (822 and 1948 kg $CO_{2equiv.}$ ha^{-1} yr^{-1}, respectively), implying net GHG emission to the atmosphere (Table 3). Conversely, net GWP for SW-S-R was negative (−14 kg $CO_{2equiv.}$ ha^{-1} yr^{-1}), implying net GHG uptake. However, net GWP did not differ among cropping systems (P = 0.17), nor did yield-scaled GWP (P = 0.16) (Table 3).

4. Discussion

Cropping systems evaluated in this study contributed to highly variable responses in SOC stocks and soil-atmosphere N_2O flux, two factors that typically control net GWP in agroecosystems [1]. Variation in these two factors limited conclusive inferences from hypotheses generated for the study. Though greater crop diversity resulted in lower net GWP in SW-S-R, it did not differ significantly from net GWP in less diverse cropping systems. Accordingly, the first hypothesis for the study was not supported. Study results as applied to the second hypothesis were mixed, as SOC accrual in SW-S-R did offset $CO_{2equiv.}$ emissions associated with soil-atmosphere N_2O flux, input production and field operations, while SOC accrual in CSW provided only a marginal offset of positive $CO_{2equiv.}$ emissions.

Previous GWP evaluations of conservation practices in semiarid regions, though limited, align with outcomes observed in this study. Sainju (2015) and Sainju et al. (2014) found continuously cropped no-tillage systems including barley (*Hordeum vulgaris* L.) and pea (*Pisum sativum* L.) mitigated GWP compared to tilled systems including chemical fallow, though evaluated treatments were net GHG sources when emission calculations were based on changes in SOC stocks. Positive net GWP for semiarid cropping systems have also been found outside the northern Great Plains of North America [6,12,13], highlighting a systemic challenge in attaining beneficial climate regulation services from these agroecosystems. While additional GWP evaluations of semiarid cropping systems are sorely needed, novel design features of this important agroecosystem may need to be considered if meaningful GHG mitigation benefits are to be achieved.

Emissions associated with N fertilizer played a dominant role in shaping net GWP outcomes in this study. Among factors associated with inputs and field operations, fertilizer production comprised most of the $CO_{2equiv.}$ emissions in CSW and SW-S-R. Moreover, N fertilizer application in these continuously cropped systems translated into annual N_2O emissions 2 to 4 times greater than emissions observed in multi-year studies elsewhere in the region [14,21]. Associated emission factors for N_2O were correspondingly large and contrasted to previous evaluations of semiarid cropping systems where factors were lower than the IPCC default value of 1% for N additions from mineral fertilizers [9,16].

Elevated N_2O emissions observed in this study were likely caused by weather-related factors and fixed fertilizer management decisions. The growing season preceding initiation of gas flux measurements was exceedingly dry, with only 188 mm received from April–September [41]. Accordingly, limitations in soil moisture during the 2006 growing season restricted crop uptake of fertilizer, contributing high levels of residual N and increased potential for conversion to N_2O (data not shown). No changes were made to reduce N fertilizer application rates in 2007 due to presence of residual N, thereby exacerbating the potential for N_2O emission. Moreover, a consistent presence of winter snow cover during each year of the study provided ideal soil moisture conditions for substantial N_2O emission events during mid-winter and/or spring thaw, underscoring the importance of conducting gas flux measurements during the non-growing season. The largest N_2O emissions observed across treatments occurred in the spring of 2009, following abundant precipitation from winter snowfall (286 mm) and an extreme precipitation event ($\geq$100 mm within 24 h) in mid-June [29,30]. Such conditions underscore the overriding influence of weather events on N_2O emissions, while concurrently highlighting the importance of adaptive management to mitigate such emissions [42].

5. Conclusions

Deployment of agroecosystems that mitigate agriculture's contribution to climate change is urgently needed. To facilitate this need, thorough evaluations are required to provide science-based guidance to select appropriate management practices to make meaningful reductions in net GWP. Given this context, we sought to determine net GWP for three semiarid cropping systems differing in cropping intensity and diversity using a combination of gas flux and SOC stock data, management records and published emission estimates for field operations and production inputs.

We found emissions associated with production inputs and field operations were generally greatest for the least diverse cropping system (CSW), intermediate for the most diverse cropping system (SW-S-R) and lowest for the cropping system with alternate years of fallow (SW-F). This trend was largely driven by N fertilizer requirements and the frequency of grain harvest within each cropping system, despite an absence of differences in $CO_{2equiv.}$ emissions from pesticide production among systems. Though there were directional differences in SOC stock change among cropping systems (two systems were SOC sinks, while one was an SOC source), no assertions could be made regarding SOC sink/source capacity due to a lack of statistical differences in SOC stocks over time or among cropping systems. All cropping systems were minor CH_4 sinks but varied considerably as N_2O sources despite an absence of statistical difference in soil-atmosphere N_2O flux among systems. In sum, net GWP and yield-scaled GWP was negative, though near zero, for SW-S-R, whereas the same parameters were positive for CSW and SW-F. However, net GWP and yield-scaled GWP did not differ significantly among cropping systems in this study.

Previous regional evaluations of net GWP have highlighted the role of management to make semiarid cropping systems smaller GHG sources, as opposed to net GHG sinks. Transitioning these cropping systems to GHG sinks will require new technology and methods to improve efficiency of N use by crops [43], thereby decreasing contributions of soil-atmosphere N_2O flux to net GWP. Concurrent to improved N management is the need for adoption of cultural practices known to increase SOC stocks well above C accrual rates typical of continuously cropped, no-tillage systems. Inclusion of perennial crops for forage and/or biofeedstock production into semiarid cropping systems can result in large increases in SOC due to abundant and deep-rooted biomass [44]. However, management practices are needed to ensure GHG mitigation benefits from SOC stock increases are retained throughout the perennial-annual rotation cycle.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-445X/8/2/32/s1, Table S1: Field operations for cropping system treatments over the course of the study.

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