The Effect of Nitrogen Fertilization and No-Till Duration on Soil Nitrogen Availability and Greenhouse Gas Emissions

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Key Words: conservation agriculture, CO_2 and N_2O fluxes, PRS™-probes, native pasture.

Abstract

With a world population now greater than seven billion, it is imperative to conserve the arable land base, which is increasingly being leveraged by global demands for producing food, feed, fibre, and fuel. A key component of sustainable agriculture involves the restoration of unproductive lands that have been rendered unsuitable for agricultural production through anthropogenic soil degradation. The objective of this study was to determine the effect of varying fertilizer N rates on soil N availability and N_2O and CO_2 emissions of three soils collected at adjacent locations with contrasting management histories: native prairie or short-term (10 years) and long-term (32 years) no-till continuous multi-crop (wheat-pea-canola) cropping systems receiving five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha) for the previous nine years. Intact soil cores were collected from each site, maintained at field capacity, and incubated (22 ^{o}C) for six weeks. Weekly assessments of soil nutrient availability and N_2O and CO_2 emissions were completed to assess the impact of prolonged variable rates of fertilizer N and duration of no-till management of degraded agricultural soil relative to an adjacent native prairie soil. At the end of the six-week incubation, there was no significant difference ($P > 0.15$) in cumulative soil N supply rate between the unfertilized long-term no-till soil and native soil. Annual fertilizer N additions of 120 kg N/ha for the previous nine years were required to restore the N supplying power of the short-term no-till soil to that of the native soil, through the build-up of mineralizable N levels. As expected, repeated applications of fertilizer N increased the residual soil N levels in the cultivated soils compared to the native soil. The estimated cumulative CO_2-C and N_2O-N emissions at the end of the six-week incubation ranged from 231.8-474.7 g/m^2 to 183.9-862.5 mg/m^2, respectively. Repeated applications of $\geq$ 60 kg N/ha supported larger N_2O-N fluxes in the long-term no-till soil compared to the unfertilized control. Highest CO_2-C fluxes from the native prairie soil are consistent with its high organic matter content and contributions from root respiration. Surprisingly, the native prairie soil N_2O-N emissions were equal to those from LTNT and STNT soils receiving repeated fertilizer N applications at typical agronomic rates and is probably characteristic of rapid denitrification rates during the dormant vegetative period after snow melt prior to the growing season within temperate native grassland environments. The use of modern no-till continuous multi-crop cropping systems, along with application of fertilizer N, enhances the soil N supplying power over the long-term through the build-up of mineralizable N and appears to be an effective management strategy for improving degraded soils, thus enhancing the productive capacity of agricultural ecosystems. However, accounting for N_2O emissions associated with repeated fertilizer N applications is imperative for properly assessing the net global warming potential of any land management system.

Introduction

When considering a global population in excess of 9 billion by 2050, it is imperative that our finite agricultural soils sustainably produce adequate food, feed, fibre, and fuel for a growing population (Pimentel and Pimentel 2000; FAO 2009; MacKenzie 2009). Soil organic matter (SOM) content is often considered the key measure of 'soil quality', because it is intimately associated with all essential physical, chemical, and biological properties controlling soil productivity and, therefore, agroecosystem health (Gregorich et al. 1994; Wood et al. 2000). Approximately 85% of the arable land in Canada is located in the western prairies (Campbell et al. 2002) and since the introduction of European settlers in western Canada and the conversion of native forests and prairie ecosystems to arable agriculture, the SOM levels in cultivated prairie soils have decreased significantly due to accelerated SOM oxidation and losses from wind, water, and tillage erosion (Tiessen et al. 1994; Pennock 2003). Over the last few decades, however, with the introduction of conservation tillage practices, in particular no-till operations, the SOM level within these degraded agricultural soils is increasing (Janzen et al. 1998; McConkey et al. 2003; VandenBygaart et al. 2003). Additionally, the use of continuous multi-crop cropping systems combined with nitrogen (N) fertilizers have been shown to further increased SOM levels in these no-till managed soils (VandenBygaart et al. 2003; Lemke et al. 2012). Notwithstanding the SOM-building nature of modern agronomic practices, an important caveat is the N_2O emissions often associated with these intensive management practices, which can more than offset the greenhouse gas mitigating benefit of sequestering more CO_2-carbon (C) in soil (Six et al. 2004; Gregorich et al. 2005). While the effect of tillage practice alone on N_2O emissions is uncertain (Helgason et al. 2005), the positive correlation between fertilizer N addition and N_2O emission is definite (Malhi et al. 2006; Helgason et al. 2005). Consequently, developing best management practices to mitigate greenhouse gas emissions, through the judicious use of fertilizer N in these no-till systems, is critical to maximizing C sequestration, while minimizing the deleterious environmental effects of excessive fertilizer N addition (Snyder et al. 2009).

Although past research has provided valuable information regarding the changes in Canadian prairie agricultural soils through cultivation and the efficacy of contemporary management practices to increase SOM levels, to our knowledge, no work has been done to assess the length of no-till management required (with or without fertilizer N amendments) to restore the nutrient supplying power of degraded soil back to its pre-cultivation native condition. The objective of this study was to determine the effect of varying fertilizer N rates on soil nutrient availability and N_2O and CO_2 emissions of three soils collected at adjacent locations with contrasting management histories: 1) native prairie, 2) short-term (10 years) and 3) long-term (32 years) no-till continuous multi-crop (wheat-pea-canola) cropping systems receiving five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha) for the previous nine years. We hypothesized that there would be more efficient retention and recycling of fertilizer N with increasing duration of no-till, through the build-up of potentially mineralizable N from the SOM (Lemke et al. 2012), thereby restoring the N supply power of the soil to levels measured in the native prairie soil. A better understanding of fertilizer N fate and its impact on the soil nutrient supplying power between short-term versus long-term no-till systems is needed to educate farmers on the magnitude of the impact of fertilizer N applications in no-till systems. Such knowledge of soil nutrient dynamics will also help determine how best to restore the nutrient supply power of degraded soils and the timeframe required to observe significant improvements, along with reducing the global warming potential of these agroecosystems. (Grant et al. 2009).

Materials and Methods

Study Site

The soil samples used in this study were collected from Agriculture and Agri-Food Canada's Jim Halford experimental site (located approximately 19 km south-east of Indian Head, Saskatchewan (103.58^{o}W, 50.42^{o}N). The study site consists of two neighbouring fields differing in their duration of no-till continuous multi-crop (wheat-pea-canola) cropping system: either short-term (10 years) or long-term (32 years), which are adjacent to a native prairie (Fig. 1). The soil at the site is a sandy loam Orthic Black Chernozem of the Oxbow Association, developed on medium-textured calcareous glacial till with gently rolling knob and kettle topography (Ellis et al. 1965). The climate is considered sub-humid continental (mean annual temperature of 2.5 ^{o}C; approximate annual precipitation and moisture deficit of 427 and 180 mm, respectively), with approximately 110 frost-free days (Lafond et al. 2011).

Experimental Design

The experimental design, cropping histories, and other pertinent agronomic information of both short-term (STNT) and long-term no-till (LTNT) fields is described in detail in Lafond et al. (2011) and a brief summary follows. Within each field, five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha)were imposed on treatment plots (3.96 x 10.7 m) arranged in a randomized complete block design and replicated three times, for a total of 15 treatment plots within each field. Near level areas within the STNT and LTNT fields were chosen to avoid the influence of water redistribution and past erosional events from confounding the data. The fertilizer N treatments consisted of granular urea (46-0-0) and monoammonium phosphate (11-52-0) blend that was either seed-placed or side-banded. The seed placed P treatments were sampled for this study. The rates of fertilizer phosphorous (P) used ranged from 10 to 15 kg P/ha, depending on the year and crop. When fertilizer P was side-banded, it was placed with the fertilizer N. The fertilizer sideband was located 2.5 cm to the side and 7.5 cm below the seed using a commercial hoe opener with individual press wheels on each opener for precise seed placement. The row spacing used during both the canola and spring wheat phases was 30.48 cm. During the nine years of the study (2002–2010), the rates of N and placement of P used were repeated on the same plots. The plots were seeded to spring wheat in 2002, 2004, 2006, 2008, and 2010, to field pea in 2003 and to canola in 2005, 2007, and 2009. During the years when canola was seeded on the plots, potassium sulfate (0-0-52-17; 88 kg/ha) was broadcast on the surface the previous fall to provide 46 kg K/ha and 15 kg S/ha.

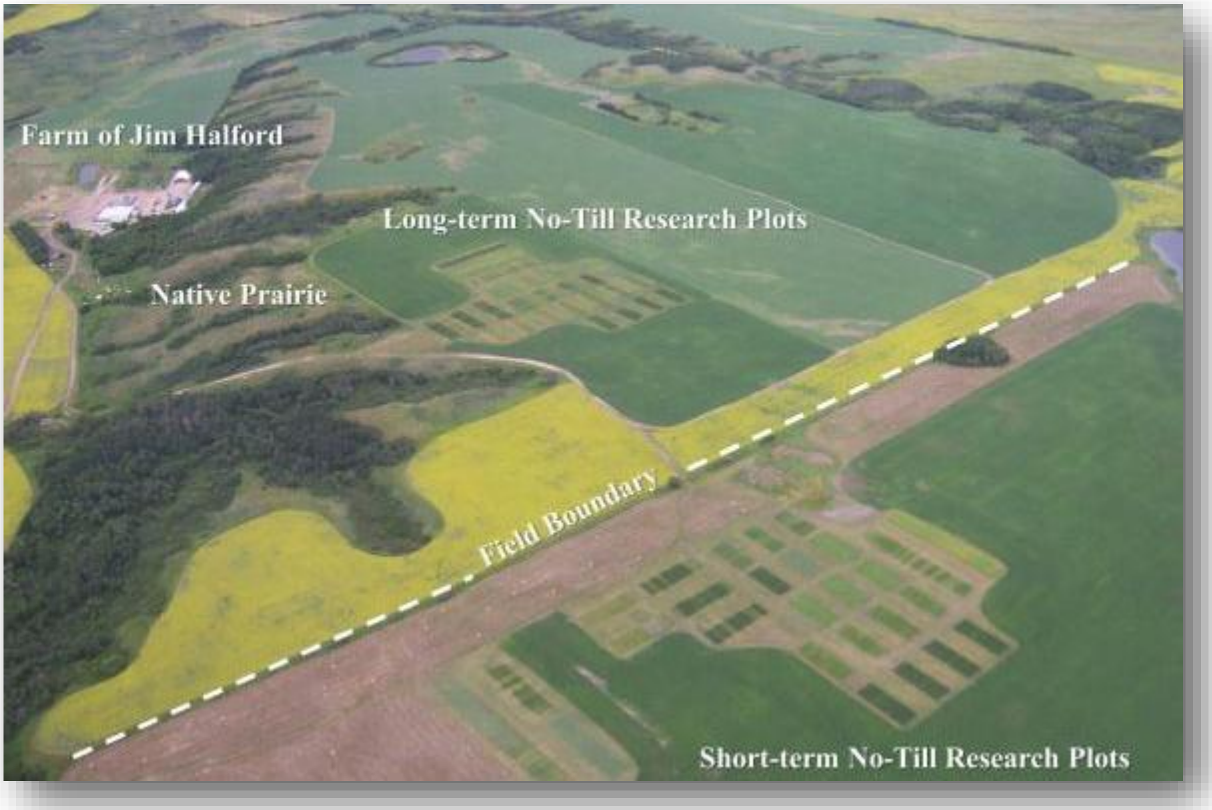

Figure 1. AAFC's Jim Halford experimental site near Indian Head, Saskatchewan.

Soil Sampling and Analyses Procedures

An intact soil core was collected from the center of each treatment plot within the STNT and LTNT fields during the spring thaw in April, using sectioned PVC pipe (10 x 15 cm) inserted into the soil and excavated (Fig. 2). A 0-15 cm depth was selected, because it is the zone of greatest SOM accumulation within no-till managed soils (Malhi et al. 2006). Four intact cores were also collected from the adjacent native prairie. All of the PVC cores were double-wrapped in plastic bags and re-frozen until the initiation of the incubation study. In addition to the intact PVC core sample, four dutch auger samples (8.5 x 15 cm) were collected at random locations immediately surrounding each extracted PVC core and composited. Each composite sample was divided in two parts; one field moist portion was sent to Western Ag Labs Ltd. (Saskatoon, SK) for a 24-hour PRS™-probe nutrient supply rate assessment (Fig. 3), with the remaining sample air-dried to constant weight, ground with a rolling pin, mixed, and sieved (< 2 mm fraction retained) before being analyzed for extractable nutrient levels (N, P, potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg)), total and organic N, total P, organic and inorganic C, and pH and EC. Total inorganic N (NO_3^--N and NH_4^+-N) and inorganic P were determined using 2.0*M* KCl (Maynard and Kalra, 2008) and modified Kelowna (Qian et al. 1994) extractions, respectively, with the extracts analyzed colourimetrically (Technicon AutoAnalyzer; Technicon Industrial Systems, Tarrytown, NY). Total N and P were determined

Figure 2. Inserting and extracting a PVC core to collect undisturbed soil for the incubation study

Figure 3. Western Ag Labs Ltd. 24-hour nutrient supply rate measurement using PRS™-probes

using a H_2SO_4/H_2O_2 digest (Thomas et al. 1967) and analyzed colourimetrically as well. Organic N was calculated from the difference between total N and inorganic N. Extractable K, Ca, and Mg were determined using 1.0*M* NH_4OAc (Hendershot et al., 2008a) and analyzed using atomic absorption (Varian Spectra 220 Atomic Absorption Spectrometer; Varian Inc., Palo Alto, CA). Extractable S was determined using 0.01*M* $CaCl_2$ (Hu et al. 2005) and analyzed using automated turbidimetry (Wall et al. 1980). Total soil C was measured using a LECO C632 Carbon Analyzer Leco (Corporation, St. Joseph, MI). Soil organic C (SOC) was likewise measured (Wang and Anderson 1998), but following a 6% H_2SO_3 pre-treatment to remove the inorganic C (Skjemstad and Baldock, 2008). Soil pH and EC (1:2 soil suspension; soil:water; Hendershot et al., 2008b) were analyzed using a Beckman 50 pH Meter (Beckman Coulter, Fullerton, CA) and a Accumet AP85 pH/EC meter (Accumet, Hudson, MA), respectively. At the end of the incubation experiment, the soil within each PVC core was removed, air-dried to constant weight, weighed, and divided by the core volume it occupied to determine bulk density.

Measuring Soil Nutrient Supply Rates During Incubation Period

The frozen PVC soil cores were placed inside of incubation chambers as described by Nelson et al. (2007) and allowed to thaw at room temperature for one week prior to commencing the six-week incubation study. During the incubation period, the soil cores were kept at room temperature (22 ^{o}C) with moisture level was maintained at field capacity using an automated water system consisting of Watermark® soil moisture sensors (Irrometer Company Inc., Riverside, CA; Spaans and Baker 1992) and a Campbell Scientific CR10X dataogger to monitor soil moisture and control irrigation timing (Fig. 4). Plant Root Simulator (PRS)™-probes (Western Ag Innovations Inc., Saskatoon, SK) were used to measure soil nutrient availability within each of the soil cores during the incubation and PRS™-probes provide a basis for determining fertilizer recommendations for different cereal, oil seed, pulse, and forage crops in western Canada (Fig. 5; Qian and Schoenau 2002). The PRS™-probe consists of either cation- or anion-exchange resin membrane encased in a plastic holding device and is inserted into soil to measure nutrient supply rates with minimal disturbance and have been successfully used to measure the contribution of SOM mineralization to nutrient supply in different tillage and native grassland systems (Qian and Schoenau 1995; Bontti et al. 2011). The PRS™-probes were installed at the beginning of the incubation and replaced with fresh PRS™-probes weekly for a total of six weeks. Replacing fresh PRS™-probes in the same soil slot provides a more accurate *in situ* measure of temporal nutrient availability and yields a reliable index of potential nutrient supply over the entire measurement period (Qian and Schoenau 2002). The regeneration and analysis of the PRS™-probes followed the protocol reported in Hangs et al. (2004). Briefly, after removal, the PRS™-probes were washed free of soil to ensure complete removal of any residual soil. The PRS™-probes were eluated with 0.5*M* HCl with the eluate analyzed for NO_3^--N and NH_4^+-N colourimetrically and P, K, S, Ca, and Mg measured using ICP (IRIS Intrepid II XSP, Thermo Fisher Scientific Inc. Waltham, MA). Continuously measuring soil solution nutrient availability provide a basis for accurately predicting nutrient supply-limited uptake or growth, because soil solution chemistry is directly controlled by the mechanisms governing nutrient supply and uptake (Lajtha et al., 1999; Smethurst 2000). An important component of any nutrient management system is the ability to quickly assess the soil nutrient supplying power in a meaningful and cost-effective manner, thereby allowing economically and environmentally appropriate fertility amendment decisions to be made in a timely manner (Grant et al. 2009).

Measuring Soil N_2O and CO_2 Fluxes During Incubation Period

Nitrous oxide-N and CO_2-C fluxes were estimated from the concentration change in the chamber headspace over a one hour period (Fig. 6). Gas samples were collected every week and the PVC soil cores were left unsealed between sampling days. Prior to collecting each sample, the chamber headspace air was mixed by flushing a 20-mL syringe several times to prevent stratification of the gases. Gas samples were collected after 30 and 60 min (C_{30} and C_{60}, respectively) with a 20 mL syringe and transferred to pre-evacuated 12 mL Exetainer™ vials (Labco Ltd., High Wycombe, UK) containing silica gel desiccant. Ambient air samples were collected at each sampling time and the mean value was used as the time zero concentration

Figure 4. Automated watering system to maintain soils at field capacity

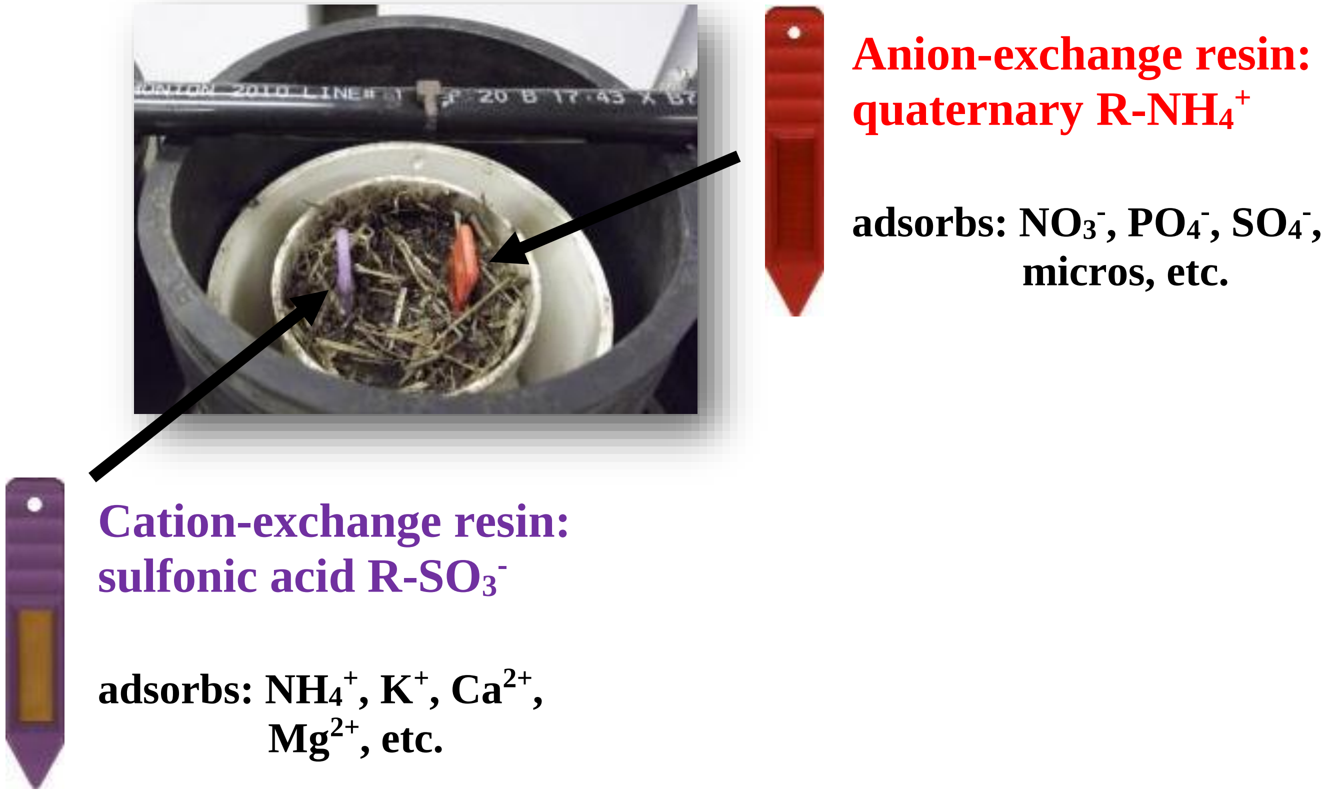

Figure 5. The use of PRS™-probes to measure soil nutrient availability during the incubation

Figure 6. The use of PRS™-probes to measure soil nutrient availability during the incubation

(C_0; Lemke et al. 1999). Gas concentrations were measured using a Varian CP3800 GC (Varian Canada Inc., Mississauga, ON) as detailed in Yates et al. (2006) and Agnew et al. (2010). Fluxes of N_2O and CO_2 were calculated as the change in gas concentration during each sampling period as described by Ginting et al. (2003) and Agnew et al. (2010). Briefly, if the ratio of $(C_{30}-C_0)/(C_{60}-C_{30}) > 1$, the fluxes were calculated according to Hutchinson and Mosier (1981); however, if the ratio was ≤ 1 then fluxes were calculated using linear or quadratic regression, depending on which model had a lower *P*-value. Cumulative gas production over the six-week incubation study was calculated by interpolating between data points and integrating over time assuming a constant flux (Lemke et al. 1999). Temperate arable and native grassland ecosystems are naturally sinks for atmospheric CH_4 (Six et al. 2004; Gregorich et al. 2005; Liebig et al. 2005; Regina and Alakukku 2010), therefore, CH_4 emissions were considered negligible from the well-drained sandy loam soils in this study.

Statistical Analyses

Measurement variables were analysed using PROC MIXED in SAS (version 9.2; SAS Institute Inc., Cary, NC., USA). The effect of field management and fertilizer N rate were considered fixed and replicate (nested within field history) was considered random. Means comparisons were performed using least significant differences (LSD; equivalent to Fisher's protected LSD) at a significance level of either 0.10 (soil property variables) or 0.15 (N_2O and CO_2 gas fluxes), with groupings obtained using the pdmix800 SAS macro (Saxton 1998). Normality of distributions (PROC UNIVARIATE) and homogeneity of variances (Bartlett's test) of all data sets were checked and when required the data was Log_{10} transformed prior to analysis. Logistical constraints necessitated the use of only three replications per each no-till x fertilizer N rate and four replications of the native soil. Consequently, given the considerable spatial variability in soil properties and N_2O/CO_2 emissions throughout any given landscape (Mosier et al. 1996; Liebig et al. 2005; Janzen et al. 1998), we felt it was prudent to use less rigorous alpha levels in the statistical analyses, in order to avoid making a type II error (Peterman 1990).

Results and Discussion

Soil Physical, Chemical, and Nutrient Data

Past management history affected the levels of inorganic carbon and total P, in addition to the extractable levels and PRS™-probe supply rates of Total N (specifically NO_3^--N) and P (Tables 1-4). Soil inorganic C levels (SIC) were higher in the STNT compared to the LTNT and native soil and the amount of inorganic C increased in STNT and LTNT soils with increasing fertilizer N rate (data not shown). The accumulation of SOM and accelerated soil genesis within the LTNT compared to the STNT soil likely diluted the inorganic carbonates in these soils, thereby decreasing the percent SIC relative to STNT. Likewise, fertilization decreased the measured SIC within the cultivated soils by increasing the SOM levels through increased residue additions following improved yields (i.e., net primary production) with increasing fertilizer N additions (Lafond et al. 2011). This presumably resulted in larger amounts of plant C inputs into these no-till systems, in particular rhizodeposition of root-derived C (Gale and Cambardella 2000). These differences in SIC among the three soils explain the observed differences in soil pH (Table 5). The lack of significant difference (P >0.10) in SOC among the three soils is intriguing, considering Lafond et al. (2011) reported greater SOC content in the LTNT and native soils compared to the STNT soil. At the time of their study, the STNT had been under no-till management for only two years, while our measurements were taken after 10 years of no-till conditions and, therefore, it is possible that the intervening period of time between our studies is a reliable indicator of the time-frame required for these no-till systems to reach steady-state SOC levels comparable to corresponding uncultivated sites (Janzen et al. 1998). Additionally, within our semi-arid environment, net losses in SOC (0- 30 cm) may be expected during the initial five years following no-till adoption, due to reduced incorporation (i.e., stratification) of crop residues relative to cultivated conditions (Six et al. 2004).

As anticipated, repeated applications of fertilizer N increased the residual soil N levels in the cultivated soils compared to the native soil (Table 5). More importantly, however, after 32 years of no-till management, the N supplying power of the unfertilized control LTNT plot soil was restored to near that of the native soil, while annual additions of 120 kg N/ha for the nine previous years to the STNT plot soil were required to achieve the same N supply rate (Table 6). The lowest amount of residual N measured in the native soil compared to the cultivated soils is not surprising given that native grassland soils typically accumulate minimal inorganic N (Dell et al. 2005). Nitrate-N was the predominant inorganic N species present in all soils (Table 6; extraction data not shown) and consequently, the direct effect of applied fertilizer N on observed residual and supply rates of Total N were also apparent with NO_3^--N. The larger NH_4^+-N supply rates within the native soil is characteristic for these low-N systems where NH_4^+-N represents a significantly larger portion of the inorganic N pool compared to cultivated soils (Schimel and Bennett 2004; Lafond et al. 2011). Increasing rates of fertilizer N addition decreased the total and extractable levels of phosphorous (Table 5) and P supply rates (Table 6) in both STNT and LTNT soils indirectly through increased P uptake concomitant with improved crop growth, as reflected in greater yields and flag leaf P content as fertilizer N rate increased (Lafond et al. 2011). Generally speaking, the extractable P levels and P supply rates of the STNT and LTNT soils were greater than the native soil due to the annual fertilizer P additions. Similarly, the lower level of extractable S in the native soil (Table 5) reflects the biennial fertilizer S additions to the STNT and LTNT plots. Notwithstanding the fertilizer S applications, the S supply rates in the 120 kg N/ha plots were smaller compared to the native soil (Table 6), which reflects the

Table 1. Summary of analysis of variance comparing the effects of nitrogen fertilization (Fert) and site management history (Site) on soil carbon (C), nitrogen (N), and phosphorus (P) levels.

Effect	df	Total C	SOC[*]	SIC[†]	Total N	SON[‡]	SIN[§]	Total P
Fert	4	0.573	0.818	0.010	0.801	0.370	0.141	0.006
Site x Fert	4	0.293	0.654	0.387	0.679	0.291	0.327	0.382

[*] Soil organic C.

[†] Soil inorganic C.

[‡] Soil organic N.

[§] Soil inorganic N.

[**] Significant (*P* < 0.10) effects are highlighted.

Table 2. Summary of analysis of variance comparing the effects of nitrogen fertilization (Fert) and site management history (Site) on extractable levels of soil nitrate, ammonium, phosphorus (P), potassium (K), and sulfur (S) along with selected soil chemical and physical properties.

		Extractable Levels							
Effect	df	NO_3^--N	NH_4^+-N	P	K	S	pH	EC[*]	BD[†]
Fert	4	0.037	0.168	0.022	0.250	0.293	0.299	0.778	0.624
Site x Fert	4	0.204	0.342	0.428	0.117	0.544	0.565	0.964	0.927

[*] Electrical conductivity.

[†] Bulk density.

[‡] Significant (*P* < 0.10) effects are highlighted.

Table 3. Summary of analysis of variance comparing the effects of nitrogen fertilization (Fert) and site management history (Site) on PRS™-probe nutrient supply rates of soil nitrate, ammonium, phosphorus (P), potassium (K), and sulfur (S) measured over a 24-hr period.

Effect	df	Total N[*]	NO_3^--N	NH_4^+-N	P	K	S
Fert	4	0.089	0.092	0.569	0.004	0.3131	0.6045
Site x Fert	4	0.897	0.902	0.612	0.202	0.2516	0.4028

[*] NO_3^--N + NH_4^+-N.

Table 4. Summary of analysis of variance comparing the effects of nitrogen fertilization (Fert) and site management history (Site) on PRS™-probe nutrient supply rates of soil nitrate, ammonium, phosphorous (P), potassium (K), and sulfur (S) measured over a six-week period.

Effect	df	Total N[*]	NO_3^--N	NH_4^+-N	P	K	S
Fert	4	0.0042	0.004	0.4708	0.0739	0.4492	0.2319
Site x Fert	4	0.5961	0.595	0.5342	0.8983	0.8546	0.7472

[*] NO_3^--N + NH_4^+-N.

Table 5. Mean (n = 3) selected soil physical, chemical, and nutrient properties of three adjacent sites with contrasting management histories: native prairie or short-term (10 years) and long-term (32 years) no-till continuous multi-crop (wheat-pea-canola) cropping systems receiving five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha) for the previous nine years.

							Extractable Levels						
		Total C	SOC[*]	Total N	SON[†]	Total P	N[‡]	P	K	S	pH	EC[§]	BD[**]
Site		(%)		(kg/ha)			(kg/ha)					(dS/m)	(g/cm^3)
Native		2.4abc[††]	2.1a	94.8a	90.4a	37.2bc	4.4e	19.5bc	511.4bc	1.4d	6.8d	190a	1.51a
	Rate (kg N/ha)												
STNT[‡‡]	0	3.0ab	1.8a	75.4ab	65.0ab	45.6ab	10.4cd	26.9abc	602.6ab	2.2c	7.8a	268a	1.46a
	30	3.1a	1.7a	69.3ab	59.6ab	37.9abc	9.7d	17.0bc	502.5bc	2.3bc	7.7a	267a	1.40a
	60	2.4bc	1.6a	72.8ab	60.9ab	35.2bc	11.9abcd	13.3bc	596.5ab	2.5bc	7.5abc	236a	1.44a
	90	2.6abc	2.1a	83.4a	70.3ab	36.9bc	13.1abcd	15.8bc	693.3a	2.8abc	7.5abc	218a	1.43a
	120	2.4bc	1.8a	75.2ab	60.7ab	32.0c	14.5ab	12.6c	684.7a	2.9abc	7.7ab	214a	1.44a
LTNT[§§]	0	2.3bc	1.5a	67.7ab	54.4ab	50.9a	13.2abcd	41.2a	398.4cd	2.7bc	7.7a	214a	1.57a
	30	2.0c	1.6a	61.3b	47.1b	30.1c	14.1ab	35.2ab	445.3bc	3.4a	7.3abcd	184a	1.49a
	60	2.0bc	1.6a	72.3ab	60.8ab	35.3bc	11.5abcd	27.2abc	416.2cd	3.1ab	7.4abcd	226a	1.55a
	90	2.0bc	1.5a	61.6b	49.0b	33.5c	12.6abcd	21.3bc	334.9d	3.4a	7.0bcd	168a	1.47a
	120	2.0bc	1.7a	77.3ab	62.0ab	34.1bc	15.3a	27.5abc	521.4abc	3.0abc	6.8cd	176a	1.57a

[*] Soil organic carbon.

[†] Soil organic nitrogen.

[‡] NO_3^--N + NH_4^+-N.

[§] Electrical conductivity.

[**] Bulk Density.

[††] Within each column, values having the same letter are not significantly different ($P > 0.10$) using LSD.

[‡‡] Short-term no-till.

[§§] Long-term no-till.

Table 6. Mean (n = 3) PRS™-probe nutrient supply rates (24-hr and cumulative six-week measurements) of three adjacent sites with contrasting management histories: native prairie or short-term (10 years) and long-term (32 years) no-till continuous multi-crop (wheat-pea-canola) cropping systems receiving five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha) for the previous nine years.

Site	Rate (kg N/ha)	Total N[*]	P	K	S	Total N	P	K	S
		(μg/10 cm^2/24-hr)				(μg/10 cm^2/six weeks)			
Native		--[†]	--	--	--	816.2abc	10.4c	1498.8a	601.9a
STNT[§]	0	37.0b[‡]	6.5a	145.8ab	4.5ab	497.7de	23.9ab	891.0b	530.9ab
	30	39.7b	1.9cde	108.9ab	2.9ab	372.3e	75.0ab	867.4b	349.0c
	60	41.1b	1.2e	94.5b	2.0b	478.4de	26.3ab	1196.9ab	502.6abc
	90	61.2ab	1.6de	160.8a	3.3ab	437.3de	33.3ab	1434.6ab	468.7abc
	120	72.5ab	1.4e	148.7a	2.0b	746.4abc	10.5c	1186.2ab	431.0bc
LTNT[**]	0	43.9b	6.7ab	100.5ab	2.7ab	702.1bcd	34.9ab	1551.8ab	387.3bc
	30	74.3ab	7.6a	133.4ab	10.4a	558.5cde	33.8ab	1608.3ab	359.9c
	60	55.2ab	4.1abc	126.7ab	2.5ab	583.0cde	45.1a	1502.9ab	493.9abc
	90	73.2ab	3.7bcd	110.9ab	3.1ab	806.3abc	25.3abc	1734.8a	484.1abc
	120	90.3a	3.1bcd	143.7ab	6.7a	918.8a	17.1c	1966.5a	381.4bc

[*] NO_3^--N + NH_4^+-N.

[†] Not measured.

[‡] Within each column, values having the same letter are not significantly different ($P > 0.10$) using LSD.

[§] Short-term no-till.

[**] Long-term no-till.

decreased S supply power of these cultivated soils, especially when frequently supporting the growth of a S-demanding crop like canola. It is important to note that studies reporting management-induced changes in SOM and nutrient levels often present erroneous conclusions, because the inferences made are based on comparisons of SOC levels derived from unequal soil masses (Ellert and Bettany 1995). Nevertheless, there were no differences ($P > 0.10$) in bulk density among the sites in this study (Table 5) to confound neither the SOC and nutrient results nor their interpretation.

Soil CO_2-C and N_2O-N Flux Data

As expected, there was considerable variability in measured CO_2-C and N_2O-N fluxes among the soils in this study. The estimated cumulative emissions at the end of the six-week incubation ranged from 231.8-474.7 g/m^2 to 183.9-862.5 mg/m^2, respectively (Table 7) and are within the range of published values (Grant and Pattey 1999; Liebig et al. 2005; Rochette 2008). After two weeks, approximately 40% of the cumulative six-week CO_2-C total flux occurred from all soils, compared to 80% of the N_2O-N flux (Figs. 7-10). Generally speaking, the CO_2-C emissions during the incubation period were linear in nature compared to the asymptotic release of N_2O-N, which is characteristic of rapid denitrification rates in following snowmelt and spring-thaw, when N_2O-N emissions can account for 50-98 % of annual losses from agricultural soils (Maggiotto and Wagner-Riddle 2001; Kurganova and Lopes de Gerenyu 2010). There were few differences in CO_2-C flux among the soils with the largest emissions from the native soil, consistent with its high organic matter content and contributions from root respiration. Native grassland soils have been shown to possess elevated, greater labile C pools, microbial biomass and activities and, therefore, greater respiration than no-till and conventionally tilled soils (Carpenter-Boggs et al. 2003; Purakayastha et al. 2009). The similarity in CO_2-C fluxes among the no-till soils reflects the similarities in SOM and microbial activity between them. Although there were no consistent differences in cumulative N_2O-N and CO_2-C emissions at the end of the six- week incubation between the soil types, it was apparent that the highest rates of fertilizer N addition in the LTNT treatment plots resulted in greater N_2O-N flux compared to the unfertilized control (Table 7), which is consistent with other studies (Malhi et al. 2006; Snyder et al. 2009; Van Groenigen et al. 2010). Moreover, the N_2O-N emissions within LTNT plots receiving at least 60 kg N/ha were greater than the STNT plots receiving the same fertilizer N rates (Table 7) and is likely indicative of the higher rates of N cycling, including processes like nitrification, within the LTNT soils (Lafond et al. 2011). Specifically, at the beginning of the incubation, the 60 kg N/ha rate was the threshold application rate where the direct effects of added fertilizer N could be statistically discerned (Figure 7). The initiation of increased N_2O-N emissions in these soils agrees with the N budget work of Lafond et al. (2011), who reported that repeated applications of $\geq$ 60 kg N/ha lead to surplus N in the LTNT plots (i.e., fertilizer N additions in excess of crop growth requirement). Despite the surplus N input, they did not find a build-up of residual inorganic N in either the STNT or LTNT soil, even after eight consecutive years of 120 kg N/ha additions. They speculated that the unnecessary fertilizer N remained within the system immobilized within crop residues and soil microbial biomass; however, it appears that some portion of it was probably lost from the system via denitrification given the fertilizer N-induced increase in N_2O-N flux we measured in those same soils.

Table 7. Mean (n = 3) estimated cumulative CO_2-C and N_2O-N fluxes from soils of three adjacent sites with contrasting management histories: native prairie or short-term (10 years) and long-term (32 years) no-till continuous multi-crop (wheat-pea-canola) cropping systems receiving five fertilizer N rates (0, 30, 60, 90, and 120 kg N/ha) for the previous nine years.

Site	Rate (kg N/ha)	Cumulative CO_2-C Flux (g/m^2/six weeks)	Cumulative N_2O-N Flux (mg/m^2/six weeks)
Native		474.7a*	693.8abc
STNT[†]	0	245.5c	328.6abcd
	30	231.8c	306.3abcd
	60	309.5abc	184.2cd
	90	278.9bc	224.6cd
	120	263.3c	183.9d
LTNT[‡]	0	283.3abc	223.9cd
	30	452.2ab	358.2abcd
	60	324.5abc	862.5a
	90	306.4abc	814.2ab
	120	246.5c	827.3ab

[*] Within each column, values having the same letter are not significantly different (*P* >0.15) using LSD.

[†] Short-term no-till.

[‡] Long-term no-till.

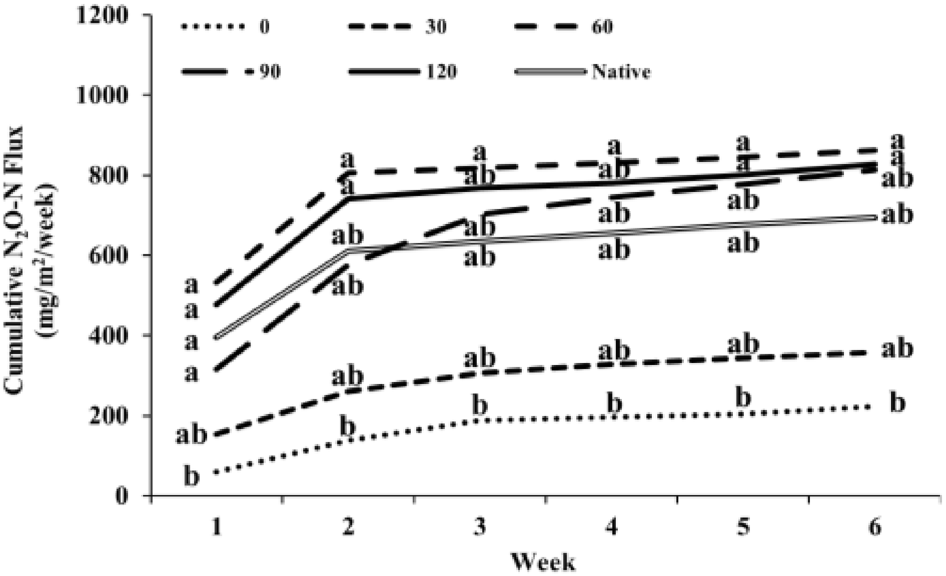

Figure 7. Mean (n = 3) estimated cumulative N_2O-N flux during a six-week incubation of soils sampled from either a native prairie or a long-term (32 years) no-till continuous multi-crop cropping system receiving five fertilizer N rates (kg N/ha) for the previous nine years. For each week, gas fluxes with the same letter are not significantly different (P >0.15) using LSD.

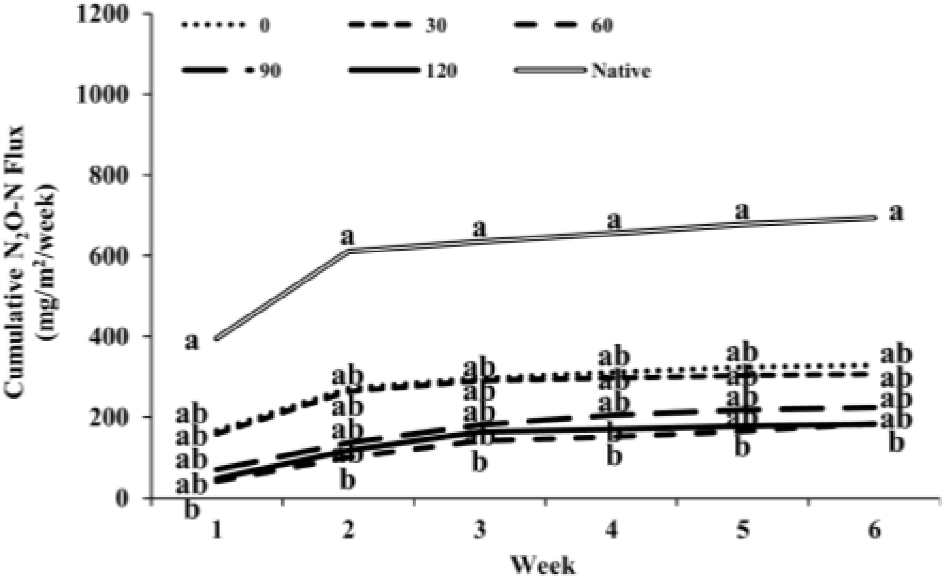

Figure 8. Mean (n = 3) estimated cumulative N_2O-N flux during a six-week incubation of soils sampled from either a native prairie or a short-term (10 years) no-till continuous multi-crop cropping system receiving five fertilizer N rates (kg N/ha) for the previous nine years. For each week, gas fluxes with the same letter are not significantly different (P >0.15) using LSD.

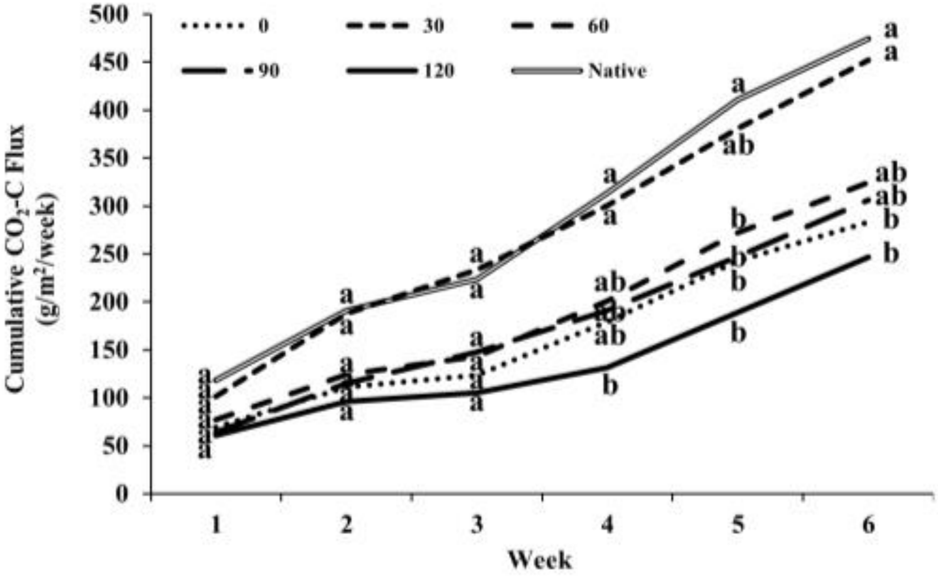

Figure 9. Mean (n = 3) estimated cumulative CO_2-C flux during a six-week incubation of soils sampled from either a native prairie or a long-term (32 years) no-till continuous multi-crop cropping system receiving five fertilizer N rates (kg N/ha) for the previous nine years. For each week, gas fluxes with the same letter are not significantly different (P >0.15) using LSD.

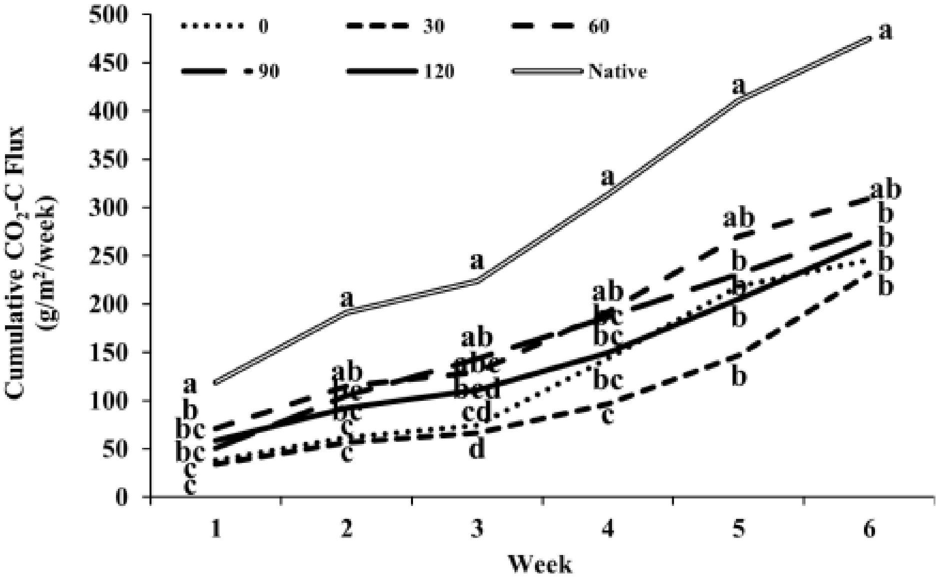

Figure 10. Mean (n = 3) estimated cumulative CO_2-C flux during a six-week incubation of soils sampled from either a native prairie or a short-term (10 years) no-till continuous multi-crop cropping system receiving five fertilizer N rates (kg N/ha) for the previous nine years. For each week, gas fluxes with the same letter are not significantly different (P >0.15) using LSD.

Perhaps the most striking results of this study were the measured N_2O-N emissions from the native prairie soil, especially when compared to fluxes from LTNT and STNT soils receiving repeated fertilizer N applications at typical agronomic rates. As already mentioned, the native soil had a relatively active microbial community and the size and activity of the soil microbial community is directly proportional to the SOM content and nutrient cycling rates (Hamel et al. 2006). There has been limited work done investigating trace gas emissions from native prairie landscapes within the Northern Great Plains, especially during the dormant season after spring-thaw prior to the growing season, due to the high degree of spatial and temporal variability within these complex ecosystems, in addition to logistical constraints of measuring trace gas fluxes in situ (Gregorich et al. 2005; Liebig et al. 2005). The three most commonly cited abiotic and biotic edaphic properties governing N_2O-N emissions are anaerobiosis, residual inorganic N, and labile SOC; all of which readily occur annually at some point in the spring within temperate native grassland environments. These factors, along with with the greater microbial biomass and activity present within these undisturbed soils could create ideal conditions exist for significant denitrification losses within these native grasslands, which comprise almost 1/3 of the earth's natural vegetation (Adams et al. 1990).

Our intact PVC soil cores were sampled immediately after snowmelt, re-frozen, and thawed for one week prior to initiating the incubation under field capacity conditions. The perennial native short-grass species within the intact cores remained dormant into the fourth week of the incubation. Although our incubation temperature was warmer than typical spring field conditions, N_2O emission peaks at the soil surface are primarily controlled by moisture-dependent diffusion-related processes rather than soil temperature maxima (Lessard et al. 1996; Wagner-Riddle et al. 1997; Wagner-Riddle and Thurtell 1998). The water-filled porosity of our sandy loam soils maintained at field capacity would have been approximately 54 % (Jarecki et al. 2008), which is close to the critical threshold of 60 % for denitrification often reported in the literature (Helgason et al. 2005; Rochette 2008; Regina and Alakukku 2010). This should represent *in situ* soil moisture conditions in the spring quite well and, therefore, our estimated N_2O-N fluxes from arable and native grassland soils should be indicative of what occurs *in situ* during the dormant vegetative period immediately after snow melt prior to the growing season. The importance of quantifying these spring-thaw N_2O-N fluxes within agricultural ecosystems, even in well-drained soils where transient denitrification can occur within anaerobic microsites, has been recognized for some time (Lemke et al. 1999; Malhi et al. 2001)

While no-till managed and native prairie soils are considered C sinks for atmospheric CO_2 (Janzen et al. 1998; Frank and Dugas 2001), accounting for all greenhouse gases is imperative for properly assessing the net global warming potential of any land use system (Lemke et al. 1999). Considering that N_2O is approximately 300 times more potent greenhouse gas compared to CO_2, N_2O emissions are chiefly responsible for the trend in net global warming potential, indicating the need for judicious fertilizer N management for promoting increased net primary productivity in arable lands while increasing SOM levels, thus supporting global warming mitigation efforts (Six et al. 2004; Snyder et al. 2009). Anthropogenic N_2O emissions in Canada are largely associated with agricultural fertilizer N use, suggesting that minimizing residual inorganic N by tailoring soil fertility management practices that properly balance crop nutritional requirement with soil nutrient supplies can serve to reduce agronomic N_2O emissions (Gregorich et al. 2005). This balanced nutrient management strategy is not only beneficial from an environmental perspective, but also economically positive for the grower. Otherwise, the favourable ability of fertilizer N to increase sequestration of atmospheric CO_2-C, through enhanced crop yields, will be more than offset by the increased N_2O emissions concomitant with inadequate fertilizer N use efficiency.

Conclusion

Modern no-till continuous multi-crop cropping systems, along with repeated applications of fertilizer N are capable of returning the SOM and nutrient supplying quality of degraded agricultural soils back to pre-cultivated conditions, as represented by adjacent undisturbed native prairie soils. An additional benefit of these systems is the capacity to build-up the active fraction of SOM of these degraded soils. Nevertheless, a balanced fertilizer N management strategy is essential to properly match crop N requirement with soil levels, for increasing fertilizer N use efficiency, in order to minimize the amount of residual inorganic N available to be lost from the system through denitrification. Such losses are not only deleterious to the environment, by offsetting the greenhouse gas mitigating efforts of fixing atmospheric CO_2-C, but also adversely affect the economic returns of the grower. The significant N_2O emissions measured in the native prairie soil are disconcerting given the aerial extent of these temperate perennial ecosystems and the limited management practices currently available for reducing the annual emissions of this potent greenhouse gas from these landscapes. However, one must not rule out the possibility that the fluxes are impacted by the disturbance during the sampling process in which the intact cores are removed from the field and the fluxes measured in the lab. Field assessments of N_2O fluxes during the dormant vegetative period after snow melt prior to the growing season are needed to validate the results of this study.

Acknowledgements

Many thanks to the Saskatchewan Agriculture Development Fund for funding; J. Halford for providing the research site; Western Ag Innovations Inc. for analyzing the PRS™-probe eluates; Craig Stevenson and Yogi Suprayogi for assisting with the statistical analyses; and C. Fatteicher, D. Hahn, T. King, F. Krijnen, D. Richman, and K. Van Rees for their logistical support.

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