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Management effects on soil CO_2 efflux in northern semiarid grassland and cropland

A.B. Frank *, M.A. Liebig, D.L. Tanaka

USDA, Agricultural Research Service, Northern Great Plains Research Laboratory, Box 459, Mandan, ND 58554, USA

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Abstract

Soil respiration is a process influenced by land use, management practices, and environmental conditions. Our objectives were to evaluate relationships between management-induced differences in soil organic carbon (SOC) and soil CO_2 efflux from continuous no-till spring wheat (*Triticum aestivum* L.), spring wheat-fallow under no-till, and a native mixed-grass prairie with grazing near Mandan, ND. A Werner–Sen–Chama soil complex (Entic Haplustoll, Typic Haplustoll, and Typic Calciustoll) was present at the grassland site and a Wilton silt loam (Pachic Haplustoll) at the cropping sites. Soil chambers were used to measure soil CO_2 effluxes about every 21 days starting 14 May 2001 to 1 April 2003. Soil water and soil temperature were measured at time of CO_2 efflux measurements. Soil organic carbon, microbial biomass carbon (MBC), and above and belowground plant biomass were measured in mid-July each year. Root biomass to 0.3 m depth of the undisturbed grassland was significantly greater (12.3 Mg ha^{-1}) than under continuous wheat (1.3 Mg ha^{-1}) and wheat-fallow (0.3 Mg ha^{-1}). Grassland SOC content of 84 Mg ha^{-1} to 0.3 m soil depth was 1.2 times greater than continuous wheat and 1.3 times greater than wheat-fallow. The MBC of the grassland was 2.2 Mg ha^{-1}, or 3.6 times greater than continuous wheat and 7.2 times greater than wheat-fallow treatments. Soil CO_2 efflux averaged 2.8 g CO_2–C m^{-2} day^{-1} for grassland, compared to 1.9 g CO_2–C m^{-2} day^{-1} for wheat fallow and 1.6 g CO_2–C m^{-2} day^{-1} for continuous wheat treatments. Although these CO_2 efflux rates were based on measurements made at intervals of about 21 days, the differences among treatments with time were rather consistent. Differences in soil CO_2 efflux among treatments could be attributed to differences in SOC and MBC, suggesting that land use plays a significant role in soil CO_2 efflux from respiration.
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Keywords: Soil respiration; Soil organic carbon; Microbial biomass; No-till; Wheat

1. Introduction

Land use influences soil organic carbon (SOC) content. Conversion of grasslands in the Great Plains of the USA to cultivated cropland has resulted in loss of 15–30% of soil organic matter (Davidson and Ackerman, 1993). Adoption of minimum- and no-till

Abbreviations: C, carbon; MBC, microbial biomass carbon; SOC, soil organic carbon

* Corresponding author. Tel.: +1 701 667 3007; fax: +1 701 667 3054.
E-mail address: franka@mandan.ars.usda.gov (A.B. Frank).

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practices has partly reversed the trend in SOC losses observed under conventional tillage using moldboard plow (Fortin et al., 1996; Dao, 1998; Curtin et al., 2000). In tillage systems, residue management affects soil CO_2 efflux by altering soil temperature and water content, both of which affect microbial population and activity (Doran, 1980; Rochette et al., 1991; Fortin et al., 1996). Soil carbon (C) loss in a conservation tillage system, where soil erosion is nonexistent, is almost entirely the product of root and microbial respiration. Grassland often contains higher amount of SOC than cultivated cropland mainly due to the absence of disturbance and an extensive fibrous root system.

Soil respiration is the process whereby CO_2 evolves from the soil surface from metabolic activity of soil microbes and roots. Reduction in soil disturbance greatly reduces soil respiratory C efflux (Rochette et al., 1991; Fortin et al., 1996; Reicosky, 1997; Dao, 1998; Curtin et al., 2000; McGinn and Akinremi, 2001) and along with C supply are the major factors determining the magnitude of soil respiration (Carpenter-Boggs et al., 2003; Lohila et al., 2003; Wang et al., 2003). Tillage practices alone strongly affect soil CO_2 efflux. Examples include: comparisons of no-till and conventional tillage to permanent grass fields showed about 50% lower soil respiration in the tillage treatments and about 50% greater microbial biomass in the grass fields (Carpenter-Boggs et al., 2003); soil CO_2 efflux during a 60-day period following a wheat crop (*Triticum aestivum* L.) was twice as great under moldboard plow tillage than no-till (Dao, 1998); small grain cropping systems in eastern Canada had soil CO_2 efflux rates 75 g C m^{-2} $year^{-1}$ greater under conventional tillage than no-till (Fortin et al., 1996); and soil CO_2 efflux was lower under continuous cropping than in a crop-fallow system under no-till due to slower decomposition of residues near the soil surface and reduced soil temperatures (Curtin et al., 2000).

Soil CO_2 efflux rates may also vary with crop species used. Daily soil respiration rates under barley (*Hordeum vulgare* L.) were nearly twice that of fallow; a result attributed to the presence of roots and higher microbial activity under barley than fallow (Akinremi et al., 1999). Soil CO_2 efflux from grasslands is generally greater than for annual crop systems. A comparison study of two grassland sites and a sorghum crop showed CO_2 efflux of 450 g C m^{-2} $year^{-1}$ from bermudagrass [*Cynodon dactylon* (L.) Pers] and 650 g C m^{-2} $year^{-1}$ from native prairie compared to 60 g C m^{-2} $year^{-1}$ from sorghum [*Sorghum bicolor* (L.) Moench] (Dugas et al., 1999). Grazing also influences soil CO_2 fluxes. A grazed mixed-grass prairie had higher efflux rates (4.3 g C m^{-2} day^{-1}) than a non-grazed mixed-grass prairie (3.5 g C m^{-2} day^{-1}) (Frank et al., 2002). Recapture of CO_2 by crops is important to net ecosystem C loss as shown when soil respiration from a corn (*Zea mays* L.) field was equivalent to about 30% of net CO_2 assimilation from photosynthesis during the growing season (Rochette and Flanagan, 1997).

There is a need to better understand seasonal respiratory CO_2 losses from soils that differ in management-induced SOC. More information is needed on rates of CO_2 efflux during the dormant period for grassland and non-crop period for cropland. Such understanding will provide information on how management practices influence net C exchange, and therefore, their role to mitigate, or contribute to, the greenhouse effect. Accordingly, we sought to evaluate soil CO_2 efflux over two crop years for a Northern Great Plains semiarid mixed-grass prairie, and continuous wheat and wheat-fallow cropping systems under no-till management. The primary objectives of this study were to (1) determine the seasonality and rates of soil CO_2 efflux from sites differing in management and SOC and (2) identify relationships of biotic (plant biomass, SOC, and microbial biomass carbon (MBC)) and abiotic (SWC and soil temperature) factors governing soil respiration.

2. Materials and methods

2.1. Site description

Study sites were located at the USDA, Agricultural Research Service, Northern Great Plains Research Laboratory at Mandan, North Dakota, USA (latitude 46°46′N, longitude 100°55′W; elevation 518 m; mean annual precipitation 404 mm; mean daily air temperature 5 °C). Treatments were a 40 ha grazed mixed-grass prairie (grassland), 0.5 ha continuous spring wheat with no-till management, and 0.5 ha spring wheat-fallow with no-till management. The two cropping sites were located approximately 3 km west of the grassland site.

The grassland site was a typical Northern Great Plains mixed-grass prairie ecosystem dominated by blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Griffiths], needle-and-thread (*Stipa comata* Trin. and Rupr.), Carex (*Carex* spp.), Kentucky bluegrass (*Poa pratensis* L.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], side-oats grama [*Bouteloua curtipendula* (Michx.) Torr.], and western wheatgrass [*Pascopyrum smithii* (Rybd.) Löve]). The grassland site was grazed at 2.6 ha per steer from about mid-May to October each year since 1916 and has not been fertilized, treated with herbicides, or burned during this time. Soil on the grassland site was of the Werner–Sen–Chama complex (loamy, mixed, superactive, frigid shallow Entic Haplustoll; fine-silty, mixed, superactive, frigid Typic Haplustoll; fine-silty, mixed, superactive, frigid Typic Calciustoll).

Soil of the cropping sites was a Wilton silt loam (fine-silty, mixed, superactive, frigid Pachic Haplustoll). The two crop sites were under cultivated agriculture for more than 30 years with the two present treatments initiated in 1993. Spring wheat was seeded in late April of each year at 3.2 million viable seeds ha^{-1} using a John Deere 750 no-till drill. Fertilization was conducted at seeding by banding 67 kg N ha^{-1} (NH_4NO_3) on the continuous spring wheat and 34 kg N ha^{-1} on the wheat-fallow. Triple superphosphate was applied at 11 kg P ha^{-1} with the seed. Weed growth in both cropping treatments was controlled through pre- and post-emergent herbicides similar to those used by local producers. Crop treatments were replicated six times. Individual plots were 9.1 m × 30.1 m.

2.2. Soil CO_2 efflux

Soil CO_2 efflux from grassland and continuous wheat treatments was measured at about 21-day intervals during approximately 13:00–15:00 h from 14 May 2001 to 1 April 2002 (year 2001) and from 14 May 2002 to 1 April 2003 (year 2002). Flux for the wheat-fallow treatment was only measured from 14 May to November each year. The low soil CO_2 efflux rate during the winter season made it impossible to make measurements on both the continuous wheat and wheat-fallow treatments during the 13:00–15:00 h period in the same day. A closed gas flow system consisting of a 1259 cm^3 cylindrical chamber with a 95 mm diameter opening, a LI-COR model 6262 infrared gas analyzer, and a LI-COR model LI-670 gas flow control unit was used to measure soil CO_2 efflux (LI-COR, Lincoln, NE). Six rings (polyvinyl chloride 104 mm diameter, 50 mm deep) were randomly placed 25 mm into the soil separated by approximately 50 m within the grazed grassland site for the duration of the study and randomly, except wheel tracks were avoided, in the cropped treatments after seeding. The initial ring locations in the prairie site contained live vegetation, but thereafter the soil surface within the collars was kept free of any live vegetation by clipping at the soil surface and by hand removal of residue. During the winter snow period the rings were covered with pots (0.3 m height, 0.2 m diameter) perforated to allow free air flow and prevent heavy accumulation of snow within the ring. Occasionally, small amounts of snow were deposited within the rings. If present, most of the snow was removed without disturbing the soil surface prior to making measurements. Flux measurements before and after snow removal from the rings showed that light snow accumulation did not affect CO_2 efflux (data not presented). Changes in CO_2 concentration within the chamber from about 15 ppm below to 15 ppm above ambient were recorded every 5 s during the growing season and every 10 s during the dormant period with a portable data logger (polycorder model 714B, Harvestmaster Inc., Logan, UT).

Frank et al. (2002) reported that efflux measurements between 13:00 and 15:00 h provided a reasonable estimate of daily efflux for a grassland site. Thus, efflux rates reported in this paper were determined by assuming linear interpolation of efflux measurements between sampling dates.

2.3. Plant biomass

Aboveground plant biomass was measured at each site by clipping four representative 0.25 m^2 quadrats at peak biomass, about mid-July each year, for the prairie and at seed maturity in early August for the wheat crop. Plant material was oven dried (70 °C) and weighed. Root biomass was estimated by taking four soil cores (66 mm diameter) to 0.3 m depth at the time of aboveground biomass sampling. A hydropneumatic elutriation system separated roots from soil (Smucker et al., 1982), which were then oven dried (70 °C), and weighed. No attempt was made to separate live and dead roots, but all non-root organic material was removed by hand.

2.4. Soil carbon and microbial biomass

Soil C content was determined from taking two 32 mm diameter cores about 0.15 m apart at 0.3 m depth, and within 1–2 m of rings used for soil flux measurements during mid-July each year. Soil from the two cores of known volume was composited in a plastic bag and subsamples were removed for determining bulk density and soil water content. Samples were processed by removing all visible root material and dried at 30 °C for 72 h, crushed to pass a 2 mm sieve, ground to 200 μm, and stored in glass bottles. Total C was determined by dry combustion using a Carlo Erba model NA1500 automatic C–N analyzer (Hake Buckler Instruments Inc., Saddle Brook, NJ), as described by Schepers et al. (1989). All soil samples had pH < 7.2, therefore total C was considered to be SOC.

Soil MBC was estimated using the microwave irradiation technique (Islam and Weil, 1998). A soil subsample was processed by sieving through a 2.0 mm sieve at field moisture content. Fifty grams of field moist soil were incubated for 10 days at 55% water-filled pore space in the presence of 10 ml of 2.0 M NaOH. Carbon dioxide content was determined by single end-point titration with 0.1 M HCl (Paul et al., 1999). Flush of CO_2–C following irradiation was calculated without subtraction of a 10-day control (Franzluebbers et al., 1999). Gravimetric data were converted to a volumetric basis by sampling depth using field measured soil bulk density (Blake and Hartge, 1986). All data were expressed on an oven-dry basis.

2.5. Soil water and temperature

Volumetric soil water was measured at time of CO_2 efflux measurements using time-domain reflectometry techniques (HyroSense System, 12 cm probes, Campbell Sci. Ltd., Logan, UT). When soils were frozen, soil water was determined using sensors (Model CS615 water content reflectometer, Campbell Sci. Ltd.) installed at 3.8 cm soil depth. Soil temperature was measured at time of efflux measurements with copper–constantan thermocouples installed at 3.8 cm soil depth.

2.6. Statistical procedures

The field plot layout was a completely randomized design at each site. Statistical analysis was conduced using SAS PROC MIXED (Littell et al., 1996). The primary objective of this study was to determine soil CO_2 efflux from sites differing in management and SOC content. The covariance structure used to fit the repeated measure was a first-order autoregressive model. Treatments and years were considered fixed effects and plots as random effects. Means were obtained with the LSMEANS statement. Significance among means was determined using SAS PDIFF procedure at $P \leq 0.01$. Since dormant period fluxes were not measured for the wheat-fallow treatment, those dates were treated as missing values in the analysis. Stepwise regression was used to evaluate the contribution of soil temperature and soil water content to soil CO_2 efflux (SAS Institute, 1989).

3. Results and discussion

Annual precipitation was 534 mm in 2001 and 288 mm in 2002, compared to the long-term average of 404 mm. Precipitation from 1 May to 17 October, the period of greatest biomass and soil microbial activity, was 375 mm in 2001 and 166 mm in 2002, compared to the long-term average of 321 mm.

Soil organic C was significantly greater for the grassland compared to the continuous wheat and wheat-fallow treatments, which were not statistically different (Table 1). Grassland SOC content was 84 Mg ha^{-1} or 1.2 times greater than continuous wheat and 1.3 times greater than the wheat-fallow. Soil MBC followed the same statistical significant pattern of treatment differences as for SOC (Table 1). Microbial biomass C of the grassland was 2.2 Mg ha^{-1}, or 3.6 times greater than for continuous wheat and 7.2 times greater than for wheat-fallow (Table 1). The magnitude of soil respiration has been shown to be strongly related to soil C availability (Carpenter-Boggs et al., 2003; Wang et al., 2003). Microbial biomass C has also been shown to be strongly related to soil respiration under field conditions (Carpenter-Boggs et al., 2003), but not always under

Table 1
Soil organic carbon (SOC), microbial biomass C (MBC), soil CO_2–C efflux, root biomass (0–0.3 m), and aboveground biomass for grassland, continuous wheat, and wheat-fallow treatments

Treatments	SOC (Mg ha^{-1})	MBC (Mg ha^{-1})	Soil CO_2–C efflux (g m^{-2} day^{-1})	Biomass (Mg ha^{-1})	
				Root	Aboveground
Grassland	84.4a[a]	2.2a	2.8a	12.3a[b]	1.5[b]
Continuous wheat	70.0b	0.6b	1.6b	1.3a	4.1
Wheat-fallow	65.6b	0.3b	1.9b	0.3b	2.3

[a] Averages followed with different letters in any column are different at 0.01 level of probability.
[b] Averages are for 2 years even though wheat-fallow has only one crop in 2 years.

controlled incubation conditions (Wang et al., 2003). The higher SOC and MBC for the grassland over the cropped sites led to higher soil respiration.

Root biomass of the undisturbed grassland to 0.3 m depth was significantly greater than continuous wheat and wheat-fallow (Table 1). Root biomass of continuous wheat represented about 12% and wheat-fallow about 3% of grassland root biomass. In contrast, aboveground biomass was greatest for continuous wheat and least for grassland (Table 1). Although aboveground biomass capable of sequestering C through photosynthesis was less in grassland than wheat, the absence of soil disturbance and presence of an extensive, perennial belowground fibrous roots system resulted in higher grassland SOC.

Volumetric soil water content was highly variable from May to October due to infrequent precipitation. Average volumetric soil water content over the growing period was 0.23 m^3 m^{-3} for grassland, 0.28 m^3 m^{-3} for continuous wheat, and 0.34 m^3 m^{-3} for wheat-fallow (Fig. 1). Soil water content was the same across all treatments in 2001 (0.28 m^3 m^{-3}) and 2002 (0.27 m^3 m^{-3}). Soil temperature was cooler by 1.3 °C under grassland throughout the growing period than for wheat-fallow (Fig. 2). Soil temperature was slightly higher across treatments in 2002 (19.4 °C) than in 2001 (18.2 °C). Previous studies have shown soil respiration from grassland (Bremer et al., 1998; Dao, 1998; Dugas et al., 1999; Frank et al., 2002; Mielnick and Dugas, 2000) and cropland (Rochette et al., 1991; Franzluebbers et al., 1995; Fortin et al., 1996) are strongly affected by soil temperature with lesser influence from soil water content. However, when accounting for the large influence of plant growth on CO_2 efflux, which confounds the effect of temperature in perennial grass ecosystems, soil water content can also greatly influence soil CO_2 efflux (Franzluebbers et al., 2002). The treatments in this study differed sufficiently in surface residue, which created soil water content and soil temperature differences that probably influenced

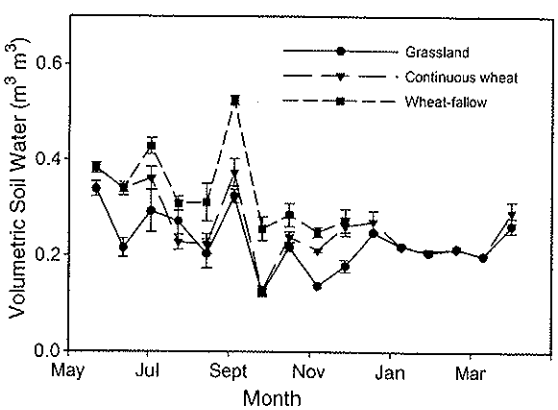

Fig. 1. Soil water content for 0–0.12 m depth averaged across 2 years for grassland, continuous wheat, and wheat-fallow. Error bars are standard error of means.

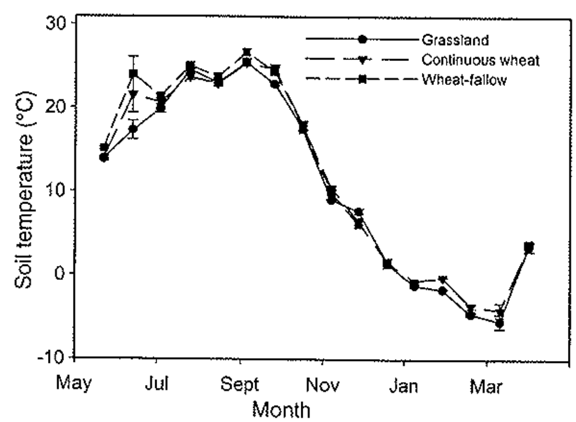

Fig. 2. Soil temperature at 3.8 cm depth averaged across 2 years for grassland, continuous wheat, and wheat-fallow. Error bars are standard error of means.

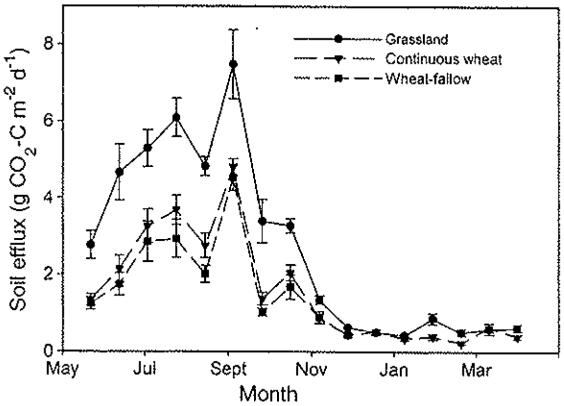

Fig. 3. Soil CO_2–C efflux averaged across 2 years for grassland, continuous wheat, and wheat-fallow. $P > F$ for treatment = 0.0002; $P > F$ for year = 0.0003; $P > F$ for treatment × year = NS. Error bars are standard error of means.

soil respiration.

Soil CO_2 efflux averaged across years was higher for grassland than continuous wheat and wheat-fallow, especially in summers (Fig. 3). Efflux from grassland was about 1.6 times greater than from wheat, averaging 2.8 g CO_2–C m^{-2} day^{-1} compared to 1.9 g CO_2–C m^{-2} day^{-1} for wheat-fallow and 1.6 g CO_2–C m^{-2} day^{-1} for continuous wheat treatments (Table 1). Dormant season (November–May) efflux was also higher for the grassland (1.0 g CO_2–C m^{-2} day^{-1}) than for continuous wheat (0.4 g CO_2–C m^{-2} day^{-1}) (dormant season measurements were not made on the wheat-fallow treatment). Year effects differed significantly with 2002, a drought year, having lower efflux (1.8 g CO_2–C m^{-2} day^{-1}) than 2001 (2.5 g CO_2–C m^{-2} day^{-1}). Although daily CO_2 efflux was based on measurements made at about 21-day intervals, efflux from grassland was consistently greater than from wheat (Fig. 3) suggesting that daily and annual efflux rates were reflective of differences between treatments.

Greater CO_2 efflux for grassland compared to cropping was strongly related to treatment differences in MBC and SOC. These results are in agreement with others who have reported that treatments containing greater amounts of available energy as C and higher MBC produced greater soil CO_2 efflux (Dugas et al., 1999; Franzluebbers et al., 2002; Carpenter-Boggs et al., 2003; Lohila et al., 2003; Wang et al., 2003). Our results compare favorably with results from perennial grass fields of bromegrass (*Bromus* spp.), wheatgrass (*Agropyron* spp.), and bluegrass (*Poa* spp.) species that had 50% greater soil CO_2 efflux and MBC than fields cropped long-term to soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and wheat (Carpenter-Boggs et al., 2003). The greater root biomass and lack of disturbance by tillage in grassland provided an energy rich C supply for microbial activity, thereby increasing CO_2 efflux. Conversely, tillage practices common in annual crop production contribute to significant efflux of soil C to the atmosphere (Reicosky, 1997).

Total estimated CO_2 efflux averaged 1.0 kg C m^{-2} $year^{-1}$ for grassland, 0.7 kg C m^{-2} $year^{-1}$ for wheat-fallow, and 0.6 kg C m^{-2} $year^{-1}$ for continuous wheat. These calculations were based on linear interpolations between dates of efflux measurements and therefore contain a level of uncertainty. However, the consistently greater efflux from grassland (Fig. 3) cannot be ignored. Even though CO_2 efflux from grassland was substantially greater than from annual cropping, the grassland had potential for C uptake by the canopy for a much longer period, i.e., about 180 days annually, compared to about 80 days for continuous wheat and only 80 days in alternate years for wheat-fallow. Significant amounts of soil C were respired to the atmosphere, even under excellent management practices, which suggests that similar to forest ecosystems (Valentini et al., 2000), soil respiration may determine net ecosystem C exchange in these Northern Great Plains ecosystems.

Soil CO_2 efflux was more strongly affected by soil temperature than soil water from stepwise regression (Table 2). The variables, MBC and SOC, were not included in regression analysis, since they were single yearly measurements, rather than the frequent measurement of soil temperature and soil water content taken at time of soil CO_2 efflux measurements. Soil temperature was the only variable to meet the model significance level for entry (0.10) for all treatments. Soil temperature produced a model R^2 of 0.55 for all three treatments, 0.62 for wheat-fallow and continuous wheat, and 0.83 for grassland alone. Soil water met model entry requirements for grassland and wheat treatments independently, but not for the combined grassland and wheat treatments. These results agree with others on the dominant effect of soil temperature on soil CO_2 efflux rates (Rochette et al., 1991; Norman et al., 1992; Lloyd and Taylor, 1994;

Table 2
Partial R^2 and equation from stepwise regression for treatment combinations of grassland, continuous wheat, and wheat-fallow using the model: daily soil CO_2–C efflux (g CO_2–C m^{-2} day^{-1}) = soil temperature (T_s), soil water content (SWC)

Treatment combinations	n	Partial R^2		Equation
		T_s	SWC	
Grassland, continuous wheat, wheat-fallow	42	0.55[a]	–	Daily soil CO_2–C efflux = 0.40 + (0.13T_s)
Continuous wheat, wheat-fallow	26	0.62	0.07[b]	Daily soil CO_2–C efflux = −0.86 + (4.55SWC) + (0.09T_s)
Grassland	16	0.83	0.05[b]	Daily soil CO_2–C efflux = −1.42 + (9.26SWC) + (0.18T_s)

[a] All partial R^2 for T_s are significant at 0.0001 level of probability.
[b] Partial R^2 significant at 0.03 level of probability.

Bajracharya et al., 2000; Mielnick and Dugas, 2000; Frank et al., 2002).

4. Conclusions

The SOC and MBC of grassland compared to cropping clearly suggest that land use plays a significant role in soil CO_2 efflux due to respiration. Although wheat produced significantly greater aboveground biomass than grasslands, grassland contributed significantly greater root biomass resulting in large amounts of SOC, and therefore greater soil CO_2 efflux. The indigenous species of grasslands had a more extensive root system than wheat. Also, grasslands sequester atmospheric CO_2 for nearly 180 days per year compared to about 80 days for spring wheat. The longer period for grassland to photosynthesize compared to wheat was considered advantageous, as this provided the potential for grassland to recapture a greater amount of respired soil CO_2 than wheat.

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