Soil Carbon Dioxide Emission and Carbon Content as Affected by Irrigation, Tillage, Cropping System, and Nitrogen Fertilization

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Management practices can influence soil CO_2 emission and C content in cropland, which can effect global warming. We examined the effects of combinations of irrigation, tillage, cropping systems, and N fertilization on soil CO_2 flux, temperature, water, and C content at the 0- to 20-cm depth from May to November 2005 at two sites in the northern Great Plains. Treatments were two irrigation systems (irrigated vs. non-irrigated) and six management practices that contained tilled and no-tilled malt barley (*Hordeum vulgaris* L.) with 0 to 134 kg N ha^{-1}, no-tilled pea (*Pisum sativum* L.), and a conservation reserve program (CRP) planting applied in Lihen sandy loam (sandy, mixed, frigid, Entic Haplustolls) in western North Dakota. In eastern Montana, treatments were no-tilled malt barley with 78 kg N ha^{-1}, no-tilled rye (*Secale cereale* L.), no-tilled Austrian winter pea, no-tilled fallow, and tilled fallow applied in dryland Williams loam (fine-loamy, mixed Typic Argiborolls). Irrigation increased CO_2 flux by 13% compared with non-irrigation by increasing soil water content in North Dakota. Tillage increased CO_2 flux by 62 to 118% compared with no-tillage at both places. The flux was 1.5- to 2.5-fold greater with tilled than with non-tilled treatments following heavy rain or irrigation in North Dakota and 1.5- to 2.0-fold greater with crops than with fallow following substantial rain in Montana. Nitrogen fertilization increased CO_2 flux by 14% compared with no N fertilization in North Dakota and cropping increased the flux by 79% compared with fallow in no-till and 0 kg N ha^{-1} in Montana. The CO_2 flux in undisturbed CRP was similar to that in no-tilled crops. Although soil C content was not altered, management practices influenced CO_2 flux within a short period due to changes in soil temperature, water, and nutrient contents. Regardless of irrigation, CO_2 flux can be reduced from croplands to a level similar to that in CRP planting using no-tilled crops with or without N fertilization compared with other management practices.

Global warming due to increased concentration of greenhouse gases, such as CO_2, in the atmosphere is a major concern. It has been estimated that agricultural practices contribute about 25% of total anthropogenic CO_2 emissions (Duxbury, 1994, 1995). Soil can act both as source and sink of atmospheric CO_2. The CO_2 fixed in plant biomass through photosynthesis can be stored in soil as organic C by converting plant residue into soil organic matter after the residue is returned to the soil. While management practices, such as tillage, can increase CO_2 emission from soil by disrupting soil aggregates, incorporating plant residue, and oxidizing soil organic C (Beare et al., 1994; Jastrow et al., 1996), no-tillage practices and increased cropping intensity can increase soil C storage (Lal et al., 1995; Paustian et al., 1995). Respiration by plant roots also contribute about half of CO_2 emitted from the soil (Rochette and Flanagan, 1997; Curtin et al., 2000). The CO_2 emission from soil to the atmosphere is the primary mechanism of soil C loss (Parkin and Kaspar, 2003) and provides an early indication of soil C level when changes in organic C due to management practices are not detectable within a short period (Fortin et al., 1996; Grant, 1997).

Reduced tillage is regarded as one of the most effective agricultural practices to reduce CO_2 emission and sequester atmospheric C in the soil (Lal and Kimble, 1997; Curtin et al., 2000; Al-Kaisi and Yin, 2005). Decreased tillage intensity reduces soil disturbance and microbial activities, which in turn, lowers CO_2 emission (Lal and Kimble, 1997; Curtin et al., 2000). Moreover, no till with surface residue can further reduce CO_2 emission compared with no till without residue (Al-Kaisi and Yin, 2005). In contrast, increased tillage intensity increases CO_2 emission by increasing aeration due to greater soil disturbance (Roberts and Chan, 1990) and to physical degassing of dissolved CO_2 from the soil solution (Jackson et al., 2003). Rewetting of dry soil due to irrigation or rainfall increased CO_2 flux by increasing microbial activities, C mineralization, and respiration (Van Gestel et al., 1993; Calderon and Jackson, 2002).

Cropping system can influence CO_2 emission by affecting the quality and quantity of residue returned to the soil (Curtin et al., 2000; Al-Kaisi and Yin, 2005; Amos et al., 2005). Increased above-

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Abbreviations: CRP, conservation reserve program; CTBFN, conventional-till malt barley with 67 to 134 kg N ha^{-1}; CTBON, conventional-till malt barley with 0 kg N ha^{-1}; CTFON, conventional-till fallow with 0 kg N ha^{-1}; DOY, day of the year; NTBFN, no-till malt barley with 67 to 134 kg N ha^{-1}; NTBON, no-till malt barley with 0 kg N ha^{-1}; NTCRP, no-till CRP planting containing alfalfa and grasses with 0 kg N ha^{-1}; NTFON, no-till fallow with 0 kg N ha^{-1}; NTPON, no-till pea with 0 kg N ha^{-1}; and NTRON, no-till rye with 0 kg N ha^{-1}.

and belowground biomass production of crops can increase the amount of residue returned to the soil (Sainju et al., 2005b), thereby increasing CO_2 flux (Curtin et al., 2000; Al-Kaisi and Yin, 2005). Increased belowground biomass production can also increase root and rhizosphere respiration, thereby increasing CO_2 flux (Amos et al., 2005). Similarly, residue quality, such as C/N ratio, can alter the decomposition rate of residue (Kuo et al., 1997; Sainju et al., 2002), thereby influencing CO_2 emission (Al-Kaisi and Yin, 2005). Although increased cropping intensity can increase CO_2 emission, it can also increase soil C storage by increasing residue C input (Curtin et al., 2000; Al-Kaisi and Yin, 2005). However, it has been reported that N fertilization had little effect on CO_2 emission from the soil surface (Rochette and Gregorich, 1998; Amos et al., 2005).

Management practices can affect soil temperature and water content (Curtin et al., 2000; Al-Kaisi and Yin, 2005) which can directly influence CO_2 flux (Bajracharya et al., 2000; Parkin and Kaspar, 2003; Amos et al., 2005). For example, tillage can dry up the soil but no tillage can conserve soil water and reduce temperature because of decreased soil disturbance and increased residue accumulation at the soil surface (Curtin et al., 2000; Al-Kaisi and Yin, 2005). The increased water content in no-tillage systems can also increase CO_2 emission in dryland soils where microbial respiration is limited by moisture stress. However, such effect of tillage on CO_2 emission in dryland soils had not been reported. Similarly, cropping system and crop type can influence soil temperature and water content compared with fallow by affecting shade intensity and evapotranspiration (Curtin et al., 2000; Amos et al., 2005).

Little is known about the combined effects of irrigation, tillage, cropping system, and N fertilization on CO_2 flux and soil C storage in dryland farming and land converted from conservation reserve program (CRP) planting to agricultural use. The CO_2 fluxes and C sequestration rates during the transition from no till to conventional till, from dryland to irrigated, or from less intensive to more intensive cropping systems could be different from the fluxes and rates when reverse trends of land management occur. We hypothesized that no-till cropping with reduced rate of N fertilization would reduce soil CO_2 flux and increase C storage compared with conventional-till cropping or fallow system with high N fertilization rate and that irrigation would increase CO_2 flux compared with no-irrigation. Our objectives were to: (i) quantify the individual and combined effects of irrigation, tillage, cropping system, and N fertilization on soil surface CO_2 flux and C content during the crop growing season in dryland cropping systems and in land converted from CRP to agricultural use, and (ii) compare CO_2 fluxes and C contents between annual cropping systems and an established CRP planting.

Materials and Methods

Experimental Sites and Treatments

Experiments were conducted in 2005 on land in transition from CRP planting to annual cropping system at Nesson Valley in western North Dakota and on a dryland farm at Rasmussen in eastern Montana. At Nesson Valley, the soil was Lihen sandy loam (sandy, mixed, frigid, Entic Haplustolls) with 720 g kg^{-1} sand, 120 g kg^{-1} silt, 160 g kg^{-1} clay, and 7.7 pH at the 0- to 20-cm depth before the initiation of the experiment in April 2005. The resident vegetation in the CRP planting for the last 20 yr was dominated by alfalfa (*Medicago sativa* L.), crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], and western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve]. At Rasmussen, the soil was Williams loam (fine-loamy, mixed, Typic Argiborolls) with 350 g kg^{-1} sand, 325 g kg^{-1} silt, 325 g kg^{-1} clay, and 7.2 pH at the 0- to 20-cm depth. Previous cropping system was spring wheat (*Triticum aestivum* L.)-fallow. Soil organic C concentration at 0- to 5- and 5- to 20-cm depths in April 2005 was 13.7 and 9.9 g kg^{-1}, respectively, at Nesson Valley and 13.3 and 10.6 g kg^{-1}, respectively, at Rasmussen.

At Nesson Valley, treatments consisted of two irrigation systems (irrigated vs. non-irrigated) and six management practices [no-till malt barley with 67 to 134 kg N ha^{-1} (NTBFN), no-till malt barley with 0 kg N ha^{-1} (NTBON), conventional-till malt barley with 67 to 134 kg N ha^{-1} (CTBFN), conventional-till malt barley with 0 kg N ha^{-1} (CTBON), no-till pea with 0 kg N ha^{-1} (NTPON), and no-till CRP planting (NTCRP) containing alfalfa and grasses with 0 kg N ha^{-1}]. The recommended N fertilization rate for irrigated no-till and conventional-till malt barley was 134 kg N ha^{-1} and for non-irrigated no-till and conventional-till malt barley was 67 kg N ha^{-1}. The difference in N rates between irrigated and non-irrigated malt barley was due to the difference in their ability to increase crop production and N uptake in irrigated and non-irrigated conditions. For conventional-till malt barley, plots were tilled with a rototiller to a depth of 10 cm in April 2005 to prepare the seed bed and to kill the resident vegetation. For no-till malt barley and pea, crops were planted with a no-till driller without disturbing the soil. The NTCRP treatment consisted of alfalfa and grasses that were continued from previous vegetation. Resident vegetation in no-till treatments, except in NTCRP, was killed by applying glyphosate [N-(phosphonomethyl) glycine] at 3.5 kg a.i. (active ingredient) ha^{-1} before crop planting in April 2005. The experiment was arranged in a randomized complete block with irrigation as the main plot and management practice as the split-plot factor. Each treatment had three replications. The size of the experimental unit was 10.6 × 3.0 m^2.

At Rasmussen, treatments included five management practices [no-till rye with 0 kg N ha^{-1} (NTRON), no-till malt barley with 78 kg N ha^{-1} (NTBFN), no-till Austrian winter pea with 0 kg N ha^{-1} (NTPON), no-till fallow with 0 kg N ha^{-1} (NTFON), and conventional-till fallow with 0 kg N ha^{-1} (CTFON)]. All treatments, except CTFON, were applied with glyphosate at 3.5 kg a.i. ha^{-1} to control weeds before planting in April 2005. Plots in NTFON were applied with glyphosate and in CTFON were tilled with rototiller frequently to control weeds. Treatments were arranged in a randomized complete block with four replications. The plot size was 30.0 × 3.0 m^2.

Crop Management

In May 2005, malt barley (cv. Certified Tradition, Busch Agricultural Resources, Fargo, ND) was planted at 3.8-cm depth at 90 kg ha^{-1} in the irrigated treatment and at 67 kg ha^{-1} in the non-irrigated treatment with a no-till drill at Nesson Valley. Similarly, pea (cv. Majorete, Macintosh Seed, Havre, MT) was planted at

200 kg ha^{-1} in irrigated and non-irrigated treatments. In irrigated malt barley, half of N fertilizer as urea (or 67 kg N ha^{-1}) was banded at planting and other half was broadcast at 4 wk after planting. In non-irrigated malt barley, all N fertilizer was banded at planting. Phosphorus fertilizer (as triple super phosphate at 25 kg P ha^{-1}) and K fertilizer (as muriate of potash at 21 kg K ha^{-1}) were banded to both malt barley and pea at planting. The amount of N, P, and K fertilizers applied to malt barley and pea were based on soil test and crop requirement. No fertilizers were applied to alfalfa and grasses in NTCRP. However, as with other management treatments in the split-plot arrangement, NTCRP in the irrigated treatment received irrigation and in the non-irrigated treatment received no irrigation. Appropriate types and amounts of herbicides and pesticides were applied to control weeds and pests during growth and after harvest of malt barley and pea. In irrigated plots, water was applied at the rate of 10 to 25 mm per application in a series of five irrigation events using a self-propelled irrigation system from 17 June to 14 July 2005 (a total of 87 mm) based on soil moisture content. In July and August 2005, malt barley and pea were hand-harvested from an area of 4.0 × 0.5 m^2 and straw (leaves and stems), after determining biomass from an area of 1.0 m^2, was returned to the soil.

At Rasmussen, rye was planted at 78 kg ha^{-1}, malt barley at 45 kg ha^{-1}, and Austrian winter pea at 101 kg ha^{-1} with a no-till drill in April 2005. Rye and Austrian winter pea were grown as summer cover crops and malt barley as a summer cash crop. At planting, N fertilizer as urea and mono-ammonium phosphate at 78 kg N ha^{-1}, P fertilizer as mono-ammonium phosphate at 29 kg P ha^{-1}, and K fertilizer as muriate of potash at 27 kg K ha^{-1} were banded to malt barley. Appropriate amounts of herbicides and pesticides were used to control weeds and pests during growth and after harvest of malt barley. No fertilizers, herbicides, or pesticides were applied to other treatments, except glyphosate at 3.5 kg a.i. ha^{-1} to kill cover crops and weeds before planting (April) and at cover crop kill (August). No irrigation was applied. In July and August 2005, malt barley grain yield was determined from an area of 30.0 × 1.5 m^2 and biomass production from an area of 1.0 m^2, after which the straw was returned to the soil. Similarly, rye and Austrian winter pea biomass was determined from an area of 1.0 m^2, after which the residue was returned to the soil.

Carbon Dioxide Flux Measurements and Soil Sampling and Analysis

Immediately after planting, soil surface CO_2 flux was measured weekly in all treatments from May to November 2005 at Nesson Valley and Rasmussen until the ground froze. All measurements were taken between 9:00 A.M. and 12:00 P.M. of the day to reduce variability in CO_2 flux due to diurnal changes in temperature (Parkin and Kaspar, 2003). The CO_2 flux was measured with an Environmental Gas Monitor chamber attached to a data logger (model EGM-4, PP System, Haverhill, MA). The chamber was 15 cm tall, 10 cm in diameter, and had capacity to measure CO_2 flux from 0 to 9.99 g CO_2–C m^{-2} h^{-1}. The chamber was placed at the soil surface for 2 min in each plot until CO_2 flux measurement was recorded in the data logger. A flag was placed as a marker in the plot where CO_2 flux was measured throughout the study period. At the time of CO_2 measurement, soil temperature near the chamber was measured from a depth of 0 to 15 cm using a probe attached to the data logger. Similarly, gravimetric soil water content was measured near the chamber by collecting soil samples from the 0- to 15-cm depth with a probe (2.5-cm diam.) every time CO_2 flux was measured. The moist soil was oven-dried at 110°C and water content was determined. Organic and inorganic C concentrations (g kg^{-1}) were determined on soil samples collected at the 0- to 20-cm depth in April and November 2005 using the high induction furnace C and N analyzer (LECO, St. Joseph, MI) by pretreating the soil with or without H_2SO_3 (Nelson and Sommers, 1996). Soil samples were collected from five places in the middle rows of the plot from 0- to 20-cm depth with a probe (5 cm i.d.), divided into three depths (0 to 5, 5 to 10, and 10 to 20 cm), composited within a depth, air-dried, and sieved to 2 mm. Organic and inorganic C contents (kg ha^{-1}) were determined by multiplying concentrations by soil depth and bulk density that was determined [using soil mass and probe diameter (5 cm)] at the time of sample collection. Daily average air temperature and total rainfall during the study period were collected from a meteorological station located within 1 km of each study site.

Data Analysis

Data for CO_2 flux and soil temperature, water, and C content were analyzed using the Analysis of Repeated Measures procedure in the MIXED model of SAS (Littell et al., 1996). Irrigation was considered as the main plot, management practice as the split plot, and date of measurement as the repeated measure treatment for analysis of data collected at Nesson Valley. Similarly, management practice was considered as the main factor and date of measurement as the repeated measure factor for analysis of data collected at Rasmussen. Means were separated by using the least square means test when treatments and interactions were significant. When treatments were significant, orthogonal contrasts were used to determine the effect of individual management practice on soil parameters. Statistical significance was evaluated at $P \leq 0.05$, unless otherwise mentioned. Regression analysis was done between CO_2 flux and average daily air temperature, soil temperature, and soil water content to determine their relationships.

Results and Discussion

Effect of Irrigation

Irrigation and its interaction with date of measurement was significant ($P \leq 0.001$) for soil temperature, water content, and CO_2 flux but irrigation × management practice × date of measurement interaction was not significant for any of these parameters at Nesson Valley. Soil temperature at 0 to 15 cm, averaged across management practices, was higher in non-irrigated than in irrigated treatment on day of the year (DOY) 176, 195, 202, 208, and 217 (Fig. 1B). In contrast, soil water content was higher in irrigated than in non-irrigated treatment on DOY 176, 202, 208, and 217 (Fig. 1C). It is not surprising to observe lower soil temperature and higher water content with irrigated treatment on these days when irrigation was done to meet the crop water requirement during periods of higher air temperature and lower rainfall (Fig. 2A and

2B). Increased water content and evaporation from the soil surface probably reduces soil temperature, as wet soil is slower to change in temperature than dry soil (Bajracharya et al., 2000; Parkin and Kaspar, 2003). Increased rainfall increased soil water content of both irrigated and non-irrigated treatments in May and June when no irrigation was done.

The CO_2 flux, averaged across management practices, increased from 31 kg CO_2–C ha^{-1} d^{-1} on DOY 122 to 427 kg CO_2–C ha^{-1} d^{-1} on DOY 188, after which it declined (Fig. 1A). The flux was higher in irrigated than in non-irrigated treatment on DOY 158, 176, 179, and 188. Increased soil water content rather than a difference in soil temperature (Fig. 1B and 1C) probably increased CO_2 flux with irrigation during these periods. Increased CO_2 fluxes after irrigation or after a heavy rain in dry soil resulting from increased C mineralization and root respiration have been observed (Van Gestel et al., 1993; Curtin et al., 2000). Since about half of soil CO_2 flux is contributed by respiration from plant roots and rhizosphere (Rochette and Flanagan, 1997; Curtin et al., 2000), it is likely that irrigation of dry soil increased root respiration and microbial activities which increased CO_2 emission. Averaged across measurement dates and management practices, irrigation decreased soil temperature by 0.8°C but increased soil water content by 6% and CO_2 flux by 15% compared with the non-irrigated treatment (Table 1).

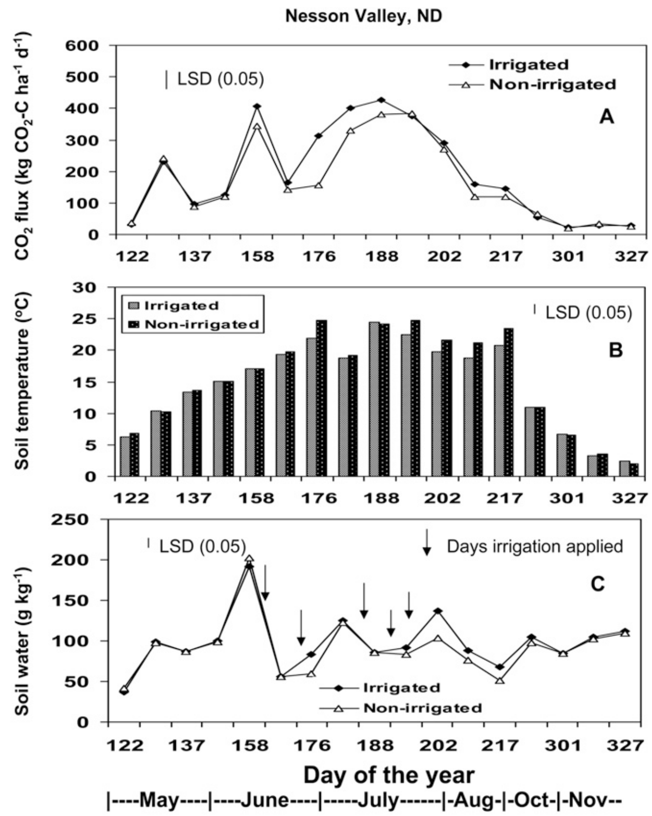

Fig. 1. (A) Effect of irrigation on soil surface CO_2 flux, (B) soil temperature, and (C) soil gravimetric water content at the 0- to 15-cm depth averaged across management practices from May to November 2005 in Nesson Valley, ND. LSD (0.05) is the least significant difference between treatments at $P \leq 0.05$. Arrows indicate time of irrigation in the irrigated treatment.

Effect of Management Practices

Nesson Valley

Management practice and its interaction with date of measurement significantly ($P \leq 0.01$) influenced soil temperature, water content, and CO_2 flux at Nesson Valley. Soil temperature at 0 to 15 cm, averaged across irrigation systems, was higher in NTCRP than in all other management practices on DOY 176, except in NTBON (Fig. 3B). Soil temperature was also higher in CTBON than in most of the other practices from DOY 195 to 217. While soil water content was consistently lower in NTCRP from DOY 137 to 158 and from DOY 202 to 217, it was higher in NTPON from DOY 144 to 166, higher in NTBON on DOY 176, 179, 202, and higher in NTBFN on DOY 208 and 217 than in most of the other practices (Fig. 3C). Averaged across measurement dates and irrigation systems, soil temperature was higher in CTBON but water content was lower in NTCRP than in other practices (Table 1). Tillage and N fertilization reduced soil temperature compared with no tillage and no N fertilization. Similarly, tillage reduced

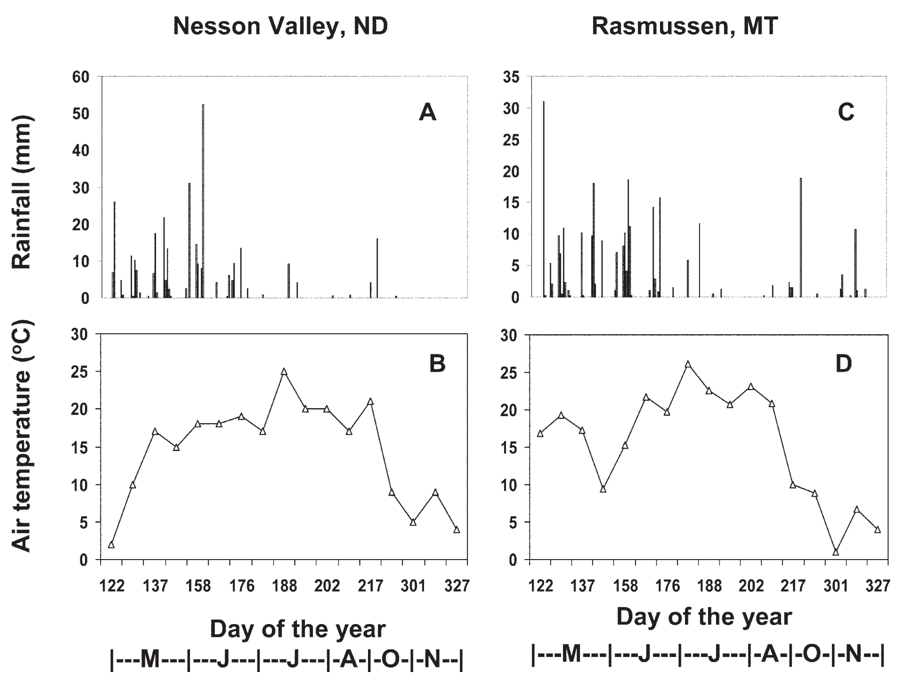

Fig. 2. (A and C) Daily total rainfall and (B and D) average air temperature at the time of CO_2 measurement from May to November 2005 in the study sites in Nesson Valley, ND and Rasmussen, MT.

Table 1. Effects of irrigation and management practices on soil surface CO_2 flux and soil temperature and water content at the 0- to 15-cm depth averaged across dates of measurement in Nesson Valley, ND.

Irrigation	Management practices (MP)†	Soil surface CO_2 flux	Soil temperature	Gravimetric soil water content
		kg CO_2–C ha^{-1} d^{-1}	°C	g kg^{-1}
Irrigated		194a‡	14.8a	97.3a
Non-irrigated		169b	15.6b	91.9b
	NTBFN (1)	164b	15.0c	97.1a
	NTPON (2)	155b	15.2b	96.5a
	CTBFN (3)	250a	15.0c	95.3a
	NTBON (4)	145b	15.2b	97.9a
	CTBON (5)	242a	15.5a	94.7a
	NTCRP (6)	160b	15.3b	86.9b
Contrasts				
Till vs. no till				
MP (3 + 5) vs. MP (1 + 4)		183***	−0.31**	−5.0*
N fertilization vs. no N fertilization				
MP (1 + 3) vs. MP (4 +5)		27*	−0.74***	−0.2
No-till barley vs. no-till pea				
MP (4) vs. MP (2)		−10	−0.02	1.3
No-till crop vs. no-till CRP in 0 kg N ha^{-1}				
MP (2 + 4) vs. MP (6)		−10	−0.08	10.3***

*, **, *** Difference between management practices means is significant at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively.

† Management practices are: CTBFN, conventional-till (CT) malt barley (B) with 67 or 134 kg N ha^{-1} (FN); CTBON, conventional-till malt barley with 0 kg N ha^{-1}(ON); NTBFN, no-till (NT) malt barley with 67 or 134 kg N ha^{-1}; NTBON, no-till malt barley with 0 kg N ha^{-1}; NTCRP, no-till conservation reserve program (CRP) planting containing undisturbed alfalfa and grasses with 0 kg N ha^{-1}; and NTPON, no-till pea (P) with 0 kg N ha^{-1}.

‡ Numbers followed by different letters within a set of a column are significantly different at $P \leq 0.05$ by the least square means test.

water content compared with no tillage but no-till cropping with 0 kg N ha^{-1} increased water content compared with CRP.

Reduced water content in NTCRP compared with other treatments from DOY 137 to 158 and from DOY 202 to 217 was probably related to greater water uptake by alfalfa and grasses than malt barley and pea during their pre-emergence and post-harvest periods when water uptake by barley and pea were negligible. Similarly, reduced water content and increased soil temperature in CTBON was likely a result of drying up of soil due to tillage and reduced plant growth. The biomass production and grain yield of malt barley were lower in CTBON than in NTBFN and CTBFN (data not shown), probably due to low N availability, since N fertilizer was not applied in this treatment. Tillage can result in drying up of soil due to increase in water vapor flux (Kessavalou et al., 1998), and decreased shading with reduced plant growth can increase soil temperature (Amos et al., 2005). In contrast, increased water content and decreased soil temperature in NTBON, NTPON, and NTBFN was probably due to reduced soil disturbance, followed by residue accumulation at the soil surface. Increased soil water content and decreased soil temperature in no till compared with conventional till have been reported by several researchers (Curtin et al., 2000; Al-Kaisi and Yin, 2005). Reduced soil temperature with N fertilization could be related to increased biomass growth which increased shading compared with no N fertilization.

With or without N fertilization, tillage increased CO_2 flux compared with no tillage at certain measurement dates, regardless of irrigation (Fig. 3A). Sharp increases in CO_2 flux occurred in tilled treatments immediately following heavy rain or irrigation on DOY 130, 158, 182, 188, 195, and 202 (Fig. 2A, 3A, and 3C) when fluxes in CTBFN and CTBON were 1.5- to 2.5-fold higher than in other treatments. The flux was also higher in NTBFN and NTPON than in NTCRP on DOY 179 but was higher in NTCRP than in NTPON on DOY 195. Similarly, the flux was higher in NTBFN than in NTBON and NTCRP on DOY 188 and higher in NTBFN and NTCRP than in NTBON on DOY 202. Averaged across measurement dates and irrigation systems, CO_2 flux was higher in CTBFN and CTBON than in other management practices (Table 1). Tillage and N fertilization increased CO_2 flux compared with no tillage and no N fertilization. Treatments did not influence soil organic and inorganic C concentrations and contents in November 2005 but organic and inorganic C concentrations decreased with soil depth (Table 2).

The CO_2 flux of as much as 300 kg CO_2–C ha^{-1} d^{-1} following tillage and heavy rain in dry soil in the northern Great Plains has been reported (Curtin et al., 2000). Our results of CO_2 flux of as much as 600 kg CO_2–C ha^{-1} d^{-1} in CTBFN and CTBON following heavy rain or irrigation seems to be extreme but could be due to tillage in the soil that had been under CRP management for more than 20 yr before the study was initiated. The effect of tillage on CO_2 flux was variable from DOY 122 to 176 depending on rainfall intensity but the flux was consistently higher in the tilled than in non-tilled treatments from DOY 179 to 202 when irrigation was applied (Fig. 2A, 3A, and 3C). Tillage can result in an immediate short-term outburst of CO_2 due to a decrease in partial pressure of CO_2 in soil air, followed by disturbance in soil aggregation and pores, and sudden release of CO_2 from the soil solution (Reicosky et al., 1995; Rochette and Angers, 1999). Under raindrop and irrigation impact, the soil surface may have sealed in the tilled treatment, temporarily trapping CO_2. As the water drained and soil surface dried, trapped CO_2 may have released in a brief, intense burst, as suggested by Curtin et al. (2000). Another possibility would be that tillage accompanied by rainfall and irrigation could have increased soil microbial activities, thereby increasing C mineralization and CO_2 flux. Better soil structure along with increased surface residue cover could have reduced surface sealing in the no-till treatment. Changes in soil organic and inorganic C contents due to CO_2 emission from May to November as a result of management practices were minor (Table 2) because only a small portion of soil organic matter mineralizes during the initial phase of tillage (Curtin et al., 2000; Al-Kaisi and Yin, 2005). Tillage also may have indirectly influenced CO_2 flux during these periods by increasing soil temperature (Fig. 3B). Although CO_2 flux can be influenced by a range of factors including soil temperature, water content, wind speed, and CO_2 concentration gradient, greater fluxes in this study than those obtained by Curtin et al. (2000) could also be due to a difference in soil texture. Soil texture in our study was sandy loam and in their study was silt loam. It has been shown that CO_2 flux increases with decreasing clay content (Parkin and Kaspar, 2003). Nevertheless, our study showed that tillage accompanied by substantial rainfall or irrigation can cause a sudden burst of CO_2 during the crop growing season from areas previously under CRP management.

The CO_2 flux was similar under malt barley and pea in the no-till system (Table 1), suggesting that cropping system did not influence CO_2 emission during the first year of study. Al-Kaisi and Yin (2005) reported no significant difference in CO_2 flux between corn (*Zea mays* L.) and soybean (*Glycine max* L.). However, in our study, lower CO_2 flux in NTCRP than in other management practices on some measurement dates was probably a result of decreased soil water content (Fig. 3A and 3C). Nitrogen fertilization increased CO_2 flux compared with no N fertilization, probably a result of increased root respiration due to increased growth. Nitrogen fertilization can increase crop root biomass compared with no N fertilization (Sainju et al., 2005a). Nitrogen fertilization can also lower the C/N ratio of the soil and increase nutrient availability which can increase microbial activities and soil respiration. Our results are in contrast to those reported by several researchers (Rochette and Gregorich, 1998; Amos et al., 2005) who found that N fertilization has little effect on CO_2 emission.

Excluding the short-term burst of CO_2 immediately after tillage (Al-Kaisi and Yin, 2005) which was not measured in this study, tilling the CRP land increased CO_2 flux roughly by an average of 183 kg CO_2–C ha^{-1} d^{-1} (Table 1) or 39.2 Mg CO_2–C ha^{-1} compared with no tillage in 214 d from May to November 2005. This measurement was based on the assumption that CO_2 flux measured in the morning from 9:00 A.M. to 12:00 P.M. would also be similar to other times of the day, which may not be true (Parkin and Kaspar, 2003). Since the accurate measurement of diurnal variation of CO_2 requires installation of equipment that automatically measure CO_2 emission every 15 min or so in each treatment (Parkin and Kaspar, 2003), which is beyond the scope of this study because of cost, time, and labor, the flux rate measured in the morning has been used to extrapolate a rough estimation of C loss as CO_2 from the soil throughout the year so that it can be compared with changes in soil organic C due to treatments. If the flux was estimated for the entire year using the same rate, it would be 66.8 Mg CO_2–C ha^{-1} yr^{-1}. This amounted to a soil C loss of 18.2 Mg C ha^{-1} yr^{-1}. The value could, however, be overestimated because CO_2 fluxes are lower in winter (December to April) than in other periods (Follett, 1997; Bajracharya et al., 2000). Furthermore, 48% of this C loss as CO_2 emission during the crop growing season from May to August (2.9 Mg C ha^{-1} yr^{-1}) would be contributed by respiration from plant roots and rhizosphere (Curtin et al., 2000), provided that root respiration during the off-season was negligible. Although soil organic and inorganic C contents in November 2005 were not influenced by treatments (Table 2), a loss of 3.1 Mg soil organic C ha^{-1} yr^{-1} occurred from April (36.4 Mg C ha^{-1} yr^{-1}) to November (33.3 Mg C ha^{-1} yr^{-1}) 2005 at the 0- to 20-cm depth. Since CO_2 can be emitted from the entire soil

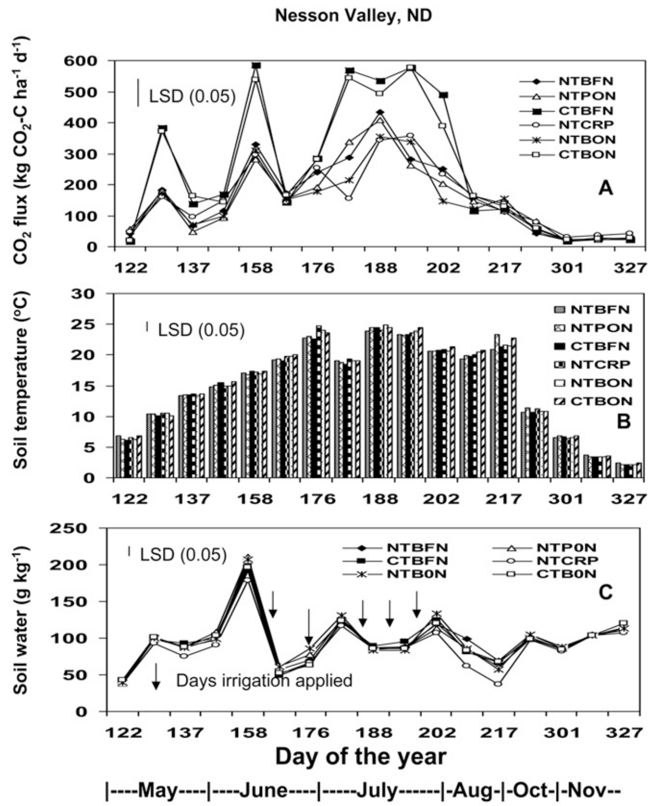

Fig. 3. Effect of management practices on (A) soil surface CO_2 flux, (B) soil temperature, and (C) soil gravimetric water content at the 0- to 15-cm depth averaged across irrigation systems from May to November 2005 in Nesson Valley, ND. Management practices are CTBFN, conventional-till malt barley with 67 or 134 kg N ha^{-1}; CTBON, conventional-till malt barley with 0 kg N ha^{-1}; NTBFN, no-till malt barley with 67 or 134 kg N ha^{-1}; NTBON, no-till malt barley with 0 kg N ha^{-1}; NTCRP, no-till conservation reserve program planting containing undisturbed alfalfa and grasses with 0 kg N ha^{-1}; and NTPON, no-till pea with 0 kg N ha^{-1}. LSD (0.05) is the least significant difference between management practices at $P \leq 0.05$. Arrows indicate time of irrigation in the irrigated treatment.

Table 2. Inorganic and organic C concentrations and contents at the 0- to 20-cm soil depth averaged across treatments in November 2005 in Nesson Valley, ND and Rasmussen, MT.

Soil depth	Concentration		Content	
	Inorganic C	Organic C	Inorganic C	Organic C
cm	g C kg^{-1} soil		Mg C ha^{-1}	
Nesson Valley, ND				
0 to 5	1.5a†	13.5a	1.1a	10.2a
5 to 10	1.3a	10.7b	0.8a	8.2a
10 to 20	1.1a	8.4c	2.2a	14.9a
0 to 20	–	–	4.1a	33.3a
Rasmusssen, MT				
0 to 5	1.3a	13.1a	0.9a	9.2a
5 to 10	1.2a	11.7b	0.9a	9.4a
10 to 20	1.1a	10.5c	1.5a	17.0a
0 to 20	–	–	3.3a	35.6a

† Numbers followed by different letters within a set of a column are significantly different at $P \leq 0.05$ by the least square means test.

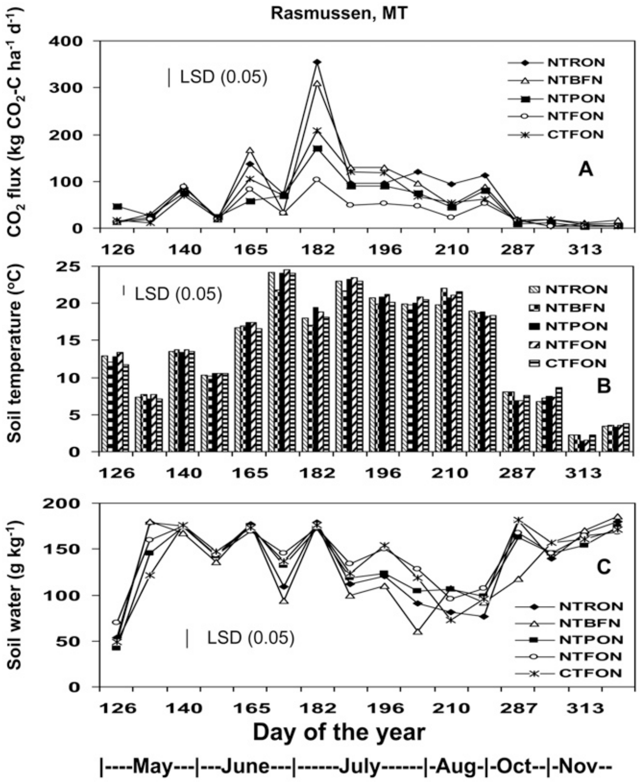

Fig. 4. Effect of management practices on (A) soil surface CO_2 flux, (B) soil temperature, and (C) soil gravimetric water content at the 0- to 15-cm depth from May to November 2005 in Rasmussen, MT. Treatments are CTFON, conventional-till fallow with 0 kg N ha^{-1}; NTBFN, no-till malt barley with 78 kg N ha^{-1}; NTFON, no-till fallow with 0 kg N ha^{-1}; NTPON, no-till Austrian winter pea with 0 kg N ha^{-1}; and NTRON, no-till rye with 0 kg N ha^{-1}. LSD (0.05) is the least significant difference between management practices at $P \leq 0.05$.

profile >20-cm depth, this loss could account for a portion of C lost as CO_2 due to mineralization of soil organic matter. The C sequestration rate in the northern Great Plains using no-till practices compared with conventional till has been estimated at 5 to 6 Mg C ha^{-1} after 13 to 14 yr or about 400 kg C ha^{-1} yr^{-1} (Curtin et al., 2000). These data show that tilling the CRP land can result in a drastic loss of soil C as CO_2 emission compared with the smaller rate of C sequestration in a year by converting tilled land into no-till system. The CO_2 emission, however, can be reduced to a level by using a no-till system similar to that in CRP planting.

Rasmussen

As in Nesson Valley, management practice and its interaction with date of measurement significantly ($P \leq 0.05$) influenced soil CO_2 flux, temperature, and water content in Rasmussen. The CO_2 flux was 1.5- to 2.0-fold higher on DOY 182 than on other days of the year in all treatments, except NTFON (Fig. 4A). The flux was higher in NTRON and NTBFN than in NTPON and NTFON on DOY 165 and 182. Similarly, the flux was higher in NTBFN and CTFON than in NTFON on DOY 189 and 196 and higher in NTRON than in NTFON from DOY 203 to 216. The flux was consistently lower in NTFON than in other treatments from DOY 182 to 216. Soil temperature at the 0- to 15-cm depth was higher in NTFON than in NTBFN from DOY 174 to 189 (Fig. 4B). Soil water content was higher in NTRON and NTBFN than in CTFON on DOY 131 but was consistently lower in NTBFN than in most of the other treatments from DOY 189 to 203 (Fig. 4C). Averaged across measurement dates, CO_2 flux was higher in NTRON than in other management practices, except in NTBFN (Table 3). In contrast, soil temperature was lower in NTBFN than in other practices, except in NTRON. The CO_2 flux was lower with legume (Austrian winter pea) than with nonlegumes (rye and malt barley) in no till and 0 kg N ha^{-1}. Cropping increased CO_2 flux but decreased soil temperature and water content compared with fallow in no till and 0 kg N ha^{-1}. Similarly, tillage increased CO_2 flux compared with no tillage in fallow and 0 kg N ha^{-1}.

Table 3. Effect of management practices on soil surface CO_2 flux and soil temperature and water content at the 0- to 15-cm depth averaged across dates of measurement in Rasmussen, MT.

Management practices (MP)†	Soil surface CO_2 flux	Soil temperature	Gravimetric soil water content
	kg CO_2–C ha^{-1} d^{-1}	°C	g kg^{-1}
NTRON (1)	79.5a‡	14.1ab	135.4a
NTBFN (2)	75.8ab	13.9b	133.7a
NTPON (3)	55.4c	14.2a	135.6a
NTFON (4)	37.6d	14.4a	143.6a
CTFON (5)	60.8bc	14.2a	138.4a
Contrasts			
Legume vs. non-legume crops in no till and 0 kg N ha^{-1}			
MP (3) vs. MP (1)	−24.1**	0.07	0.2
Cropping vs. fallow in no till and 0 kg N ha^{-1}			
MP (1 + 3) vs. MP (4)	29.8**	−0.22*	−8.0*
Till vs. no till in fallow and 0 kg N ha^{-1}			
MP (5) vs. MP (4)	23.2*	−0.18	−5.2

*, ** Difference between management practice means is significant at $P \leq 0.05$ and $P \leq 0.01$, respectively.

† Management practices are: CTFON, conventional till (CT) fallow (F) with 0 kg N ha^{-1}(ON); NTBFN, no-till (NT) malt barley (B) with 78 kg N ha^{-1}(FN); NTFON, no-till fallow with 0 kg N ha^{-1}; NTPON, no-till pea (P) with 0 kg N ha^{-1}; and NTRON, no-till rye (R) with 0 kg N ha^{-1}.

‡ Numbers followed by different letters within a set of a column are significantly different at $P \leq 0.05$ by the least square means test.

The increased CO_2 flux on DOY 165 and 182 (Fig. 4A) in all treatments, except NTFON, was likely a result of substantial rainfall in May and June 2005 (Fig. 2C), a trend similar to that observed in Nesson Valley. The greater CO_2 flux in NTRON and NTBFN than in other management practices was probably related to increased root and microbial respiration due to higher root and rhizosphere growth that may have increased substrate availability for soil microorganisms. Since aboveground biomass yield was higher in rye and malt barley than in Austrian winter pea (data not shown), it is possible that belowground biomass yield was also higher in rye and malt barley. Sainju et al. (2005b) reported that legumes produced lower root biomass than nonlegumes. As a result, legumes could have produced lower CO_2 flux than nonlegumes (Table 3). Similarly, increased CO_2 flux with cropping compared to fallow without tillage and N fertilization (Table 3) suggests that cropping may have increased root and microbial respiration. However, cropping reduced soil temperature and water content compared with fallow without tillage and N fertilization probably by increasing shading and water uptake. As in Nesson Valley, tillage increased CO_2 flux compared with no tillage in fallow and 0 kg N ha^{-1}, possibly due to mineralization of soil organic C. Conversion of tilled land into no till system probably takes more time to increase soil C storage and reduce CO_2 emission in Rasmussen compared with the sharp increase in CO_2 flux observed within a short period during the reverse trend of land conversion in Nesson Valley.

As in Nesson Valley, soil organic and inorganic C concentrations and contents were not influenced by management practices in Rasmussen. However, both organic and inorganic C concentrations decreased with soil depth (Table 2). A gain of 0.7 Mg soil organic C ha^{-1} at the 0- to 20-cm depth occurred from April (34.9 Mg C ha^{-1}) to November 2005 (35.6 Mg C ha^{-1}). If cropping was the major source of C loss through CO_2 emission compared with fallow in no till and 0 kg N ha^{-1}, an average loss of CO_2 flux at 30 kg CO_2–C ha^{-1} d^{-1} from cropping (Table 3) would roughly amount to 3.0 Mg C ha^{-1} yr^{-1}, provided that the rate of CO_2 emission measured in the morning would also be similar to the rates for other times of the day and that rates measured in the spring, summer, and fall will also be similar in the winter. Since 48% of this loss would be contributed by root respiration (Curtin et al., 2000) during the crop growing season (April to August) (0.6 Mg C ha^{-1} yr^{-1}), the loss of soil C through CO_2 emission due to cropping would roughly amount to 2.4 Mg C ha^{-1} yr^{-1}. Similarly, the loss of C through CO_2 emission due to tillage compared with no tillage in fallow and 0 kg N ha^{-1} would roughly amount to 1.9 Mg C ha^{-1} yr^{-1}. This loss is lower than the estimated C loss rate of 14.6 Mg C ha^{-1} yr^{-1} as CO_2 emission due to tillage in Nesson Valley. As increased cropping intensity and reduced tillage can increase soil C storage in dryland cropping systems (Sherrod et al., 2003; Sainju et al., 2006), the increased CO_2 flux due to cropping and tillage compared with fallow and no-tillage, respectively, will be most likely related to increased plant and microbial respiration and organic matter mineralization. Reduced tillage will, however, take a long time to increase C storage in the dryland soils of the northern Great Plains.

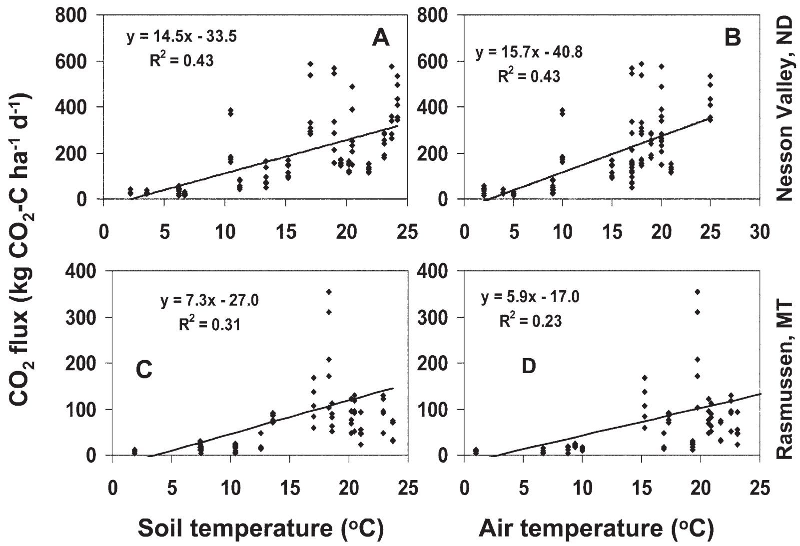

Fig. 5. Relationships between soil surface CO_2 flux and (A and C) soil temperature at the 0- to 15-cm depth and (B and D) air temperature at the time of CO_2 measurement in Nesson Valley, ND and Rasmussen, MT.

Relationship between Carbon Dioxide Emission and Temperature and Soil Water Content

Regression analysis of CO_2 flux with soil temperature at 0 to 15 cm and daily average air temperature at the time of CO_2 measurement revealed that CO_2 flux was linearly related (R^2 = 0.23 to 0.43, $P \leq 0.05$, n = 75 to 102) with both soil temperature and air temperature (Fig. 5). Both soil temperature and air temperature accounted for 23 to 43% of the variability in CO_2 flux. The CO_2 flux varied widely among treatments during the periods of substantial rainfall and irrigation in the summer, thereby resulting in some flux values as outliers at the same soil and air temperatures. Soil water content at the 0- to 15-cm depth was weakly related (R^2 = 0.15, $P \leq 0.10$, n = 75 to 102) with CO_2 flux. A stepwise regression analysis that included soil temperature and water content with CO_2 flux increased R^2 values from 0.43 to 0.65 ($P \leq 0.001$) in Nesson Valley and from 0.23 to 0.51 ($P \leq 0.01$) in Rasmusssen.

The significant relationship between CO_2 flux and soil temperature is well known (Follett, 1997; Bajracharya et al., 2000; Parkin and Kaspar, 2003). High CO_2 flux usually occurs in the summer when soil temperature is higher and soil water content and substrate C availability are adequate, while low flux occurs in the winter when soil biological activity is minimal due to freezing or near-freezing soil temperature (Follett, 1997; Bajracharya et al., 2000). Parkin and Kaspar (2003) reported that soil surface CO_2 flux was better related with air temperature than with soil temperature because of plant residue accumulation at the soil surface. Our results showed that CO_2 flux was equally or slightly better related with soil temperature than with daily average air temperature at the time of CO_2 flux measurement. The relationship was further strengthened when soil water content was taken into account along with soil temperature. Differences in management practices, such as tillage, cropping systems, N fertilization rates, and irrigation, among treatments significantly altered CO_2 fluxes even at the same soil or air temperature and soil water content. These results suggest that management practices partly modified soil temperature and water content, which in turn, influenced microbial activities, C mineralization, and respiration by roots and rhizosphere, thereby resulting in different CO_2 fluxes between treatments at various measurement dates.

Conclusions

Irrigation, soil, and crop management practices influenced soil temperature and water content, which in turn, affected soil surface CO_2 flux from transitional CRP land to cropland and cultivated drylands in the northern Great Plains. Tillage, with or without N fertilization, following substantial rain or irrigation sharply increased the CO_2 flux during the crop growing season in the transitional CRP land and following rain in dryland soils. Cropping increased CO_2 flux compared with fallow in no-tilled and non-fertilized dryland soils and N fertilization increased the flux compared with no N fertilization in the transitional CRP land. The CO_2 flux in the CRP planting was similar to that in no-till crop production. Although treatments did not influence soil C levels, the loss of C in the form of CO_2 evolved from the soil surface due to management practices accounted for a significant portion of soil C loss during the crop growing season. Within a crop growing season, CO_2 fluxes from croplands can be minimized by adopting no-tilled continuous crops with reduced N fertilization rate compared with other management practices. However, long-range studies are needed to determine the effects of management practices on CO_2 flux and soil C levels under various soil, climatic, and environmental conditions in the northern Great Plains.

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