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Carbon dioxide flux as affected by tillage and irrigation in soil converted from perennial forages to annual crops

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Abstract

Among greenhouse gases, carbon dioxide (CO_2) is one of the most significant contributors to regional and global warming as well as climatic change. A field study was conducted to (i) determine the effect of soil characteristics resulting from changes in soil management practices on CO_2 flux from the soil surface to the atmosphere in transitional land from perennial forages to annual crops, and (ii) develop empirical relationships that predict CO_2 flux from soil temperature and soil water content. The CO_2 flux, soil temperature (T_s), volumetric soil water content (θ_v) were measured every 1–2 weeks in no-till (NT) and conventional till (CT) malt barley and undisturbed soil grass-alfalfa (UGA) systems in a Lihen sandy loam soil (sandy, mixed, frigid Entic Haplustoll) under irrigated and non-irrigated conditions in western North Dakota. Soil air-filled porosity (ε) was calculated from total soil porosity and θ_v measurements. Significant differences in CO_2 fluxes between land management practices (irrigation and tillage) were observed on some measurement dates. Higher CO_2 fluxes were detected in CT plots than in NT and UGA treatments immediately after rainfall or irrigation. Soil CO_2 fluxes increased with increasing soil moisture ($R^2 = 0.15$, $P < 0.01$) while an exponential relationship was found between CO_2 emission and T_s ($R^2 = 0.59$). Using a stepwise regression analysis procedure, a significant multiple regression equation was developed between CO_2 flux and θ_v, T_s (CO_2 flux $= e^{-3.477+0.123T_s+6.381\theta_v}$; $R^2 = 0.68$, $P \leqslant 0.01$). Not surprisingly, soil temperature was a driving factor in the equation, which accounted for approximately 59% in variation of CO_2 flux. It was concluded that less intensive tillage, such as no-till or strip tillage, along with careful irrigation management will reduce soil CO_2 evolution from land being converted from perennial forages to annual crops.
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Keywords: Soil CO_2 flux; Tillage; Soil respiration; Soil air-filled porosity

1. Introduction

An increase in the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) from the soil surface to the atmosphere has been of worldwide concern over the last several decades. Carbon dioxide is recognized as a significant contributor to global warming and climatic change, accounting for 60% of global warming or total greenhouse effect (Rastogi et al., 2002). Measuring soil CO_2 flux is crucial to accurately evaluate the effect of soil management practices on global warming and carbon cycling.

Soil is considered a major source and sink for atmospheric CO_2 (Jensen et al., 1996). Soil CO_2 efflux or "soil respiration" is one of the most important components of the ecosystem C budget, which consists of organic matter decomposition and mineralization, root respiration and rhizosphere or faunal respiration (Carlisle et al., 2006). Moreover, soil contains twice the amount of C as the atmosphere and is therefore an important component of the global C budget (Mielnick and Dugas, 1999; Maier and Kress, 2000).

Studies have shown that factors such as soil temperature, moisture content, irrigation practices, tillage systems, presence of organic matter and nutrients, soil aeration, microbial processes and soil diffusivity influence CO_2 production and emission rates from the soil surface

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(Edwards, 1975; Mielnick and Dugas, 1999). Carbon dioxide emissions resulting from respiration are often stimulated by tillage (Roberts and Chan, 1990); moreover, reduced or no-tillage systems decrease CO_2 emissions, thereby increasing the storage of carbon in the soil (Kern and Johnson, 1993; Ball et al., 1999).

Interest in soil properties and management practices that control soil CO_2 respiration is growing because of the potential for climatic change (soil temperature, moisture content, irrigation and precipitation) to affect net soil CO_2 productivity and exchange between soil and atmosphere (Davidson et al., 1998). Soil temperature and moisture content are the characteristics that most commonly impact temporal variation in CO_2 efflux from soils.

Land management practices can influence soil temperature and moisture content (Curtin et al., 2000; Al-Kaisi and Yin, 2005) which can directly affect CO_2 fluxes from the soil surface (Bajracharya et al., 2000; Parkin and Kaspar, 2003; Amos et al., 2005). For example, tillage can dry the soil but no-till (NT) system can conserve soil water and reduce temperature because of decreased soil disturbance and increased residue accumulation at the soil surface (Curtin et al., 2000, 2002; Al-Kaisi and Yin, 2005).

Soil temperature is thus an important factor in controlling major processes in the C cycle; it exhibits large amplitude in its effects on CO_2 emission rates from the soil surface under field conditions. An increase in soil temperature accelerates organic matter decomposition, oxidation, microbial and root activity, and C mineralization processes. This acceleration thereby increases CO_2 emission from the soil, which in turn causes a depletion of C storage. Both root and microbial sources of CO_2 show an exponential increase in activity as a function of temperature (Boone et al., 1998; Davidson et al., 1998).

Soil moisture content affects soil respiration; higher moisture content provides better conditions for microbial habitat activities, increasing microbial oxygen consumption and CO_2 production and emission from the soil (Buyanowski and Wagner, 1983). The relationship between soil CO_2 emission and soil moisture content is not yet clearly understood. However, the effect of soil moisture content has been described by linear, quadratic, logarithmic and parabolic equations of soil water, expressed as gravimetric water content, volumetric water content, water holding capacity and matric potential (Davidson et al., 2000). Several studies have clearly demonstrated that moisture content is an important factor in soil respiration. Davidson et al. (2000) showed that rates of soil respiration increase with rising water content in both pasture and forest soil; they developed an empirical regression equation that describes soil respiration as a function of soil matric potential and concluded that CO_2 flux increases as soil matric potential decreases. Bottner (1985) and Kieft et al. (1987) indicated that high soil respiration rates may have been a function of wet-up effects, which have been demonstrated to produce pulses of microbial activity and CO_2 production.

Tillage loosens the soil, increases the exposure of soil organic matter and speeds up organic matter oxidation, intensifying CO_2 emission from the soil to the atmosphere. Tillage accelerates soil CO_2 emission by improving soil aeration, disaggregating soil, increasing the contact between soil and crop residue, and speeding organic C decomposition (Logan et al., 1991; Angers et al., 1993; Al-Kaisi and Yin, 2005). So et al. (2001) found that adoption of conservation tillage reduced CO_2 emission from the soil by 4.3 Mt yr^{-1} relative to the release that would occur under conventional tillage (CT), effectively increasing the potential for C retention.

Little research has been done to investigate the effects of management practices on CO_2 emission in transitional land. The site is a new research area that has been in rainfed crested wheatgrass-alfalfa (*Agropyron cristatum* (L.) Gaertn. and *Medicago sativa* L., respectively) hay production for over 20 years and was converted into a long-term irrigated cropping systems study. Thus, the site was selected because it presents an opportunity to study the effects of various agricultural management systems on the soil surface CO_2 fluxes in transitional land. The CO_2 emission from conversion of NT to CT, from dryland to irrigated cropping system.

The objectives of this study were (i) to determine the effect of soil characteristics resulting from changes in soil management practices on CO_2 flux from the soil surface to the atmosphere in transitional land from perennial forages to annual crops, and (ii) to develop empirical relationships that predict CO_2 flux from soil temperature and soil water content.

2. Materials and methods

2.1. Soil description, site characterization and treatments

This study was begun in the spring of 2005 at the USDA-ARS Nesson Valley Research Farm located approximately 23 miles east of Williston, ND (48.1640N, 103.0986W). The soil is classified as a Lihen sandy loam (sandy, mixed, frigid Entic Haplustoll), consisting of very deep, somewhat excessively or well drained soil. Particle size distribution analysis indicated that the textural class of the surface horizon (0–20 cm) fell consistently within the sandy loam classification.

This study consisted of two irrigation treatments (overhead-sprinkler irrigated vs. non-irrigated) and three tillage treatments [no-till with malt barley (NT), conventional tillage with malt barley (CT), and undisturbed grass-alfalfa (UGA)]. For CT, plots were tilled with a rototiller to a depth of 10 cm in April 2005 to prepare the seedbed and to kill the resident vegetation (Sainju et al., 2006). The UGA treatment consisted of alfalfa and grasses that were continued from previous vegetation. Resident vegetation in NT plots, with the exception of the UGA treatment, was killed by applying glyphosate [*N*-(phosphonomethyl) glycine)] at 3.5 kg a.i. (active ingredient) ha^{-1} prior to crop planting. The experiment was designed as a split-plot arrangement of a randomized complete block with irrigation as the main plot and tillage practice as the split-plot treatment. Each treatment had three replications and the size of the experimental unit was 3.0 m × 10.7 m (Sainju et al., 2006).

2.2. Measurement of CO_2 flux

Soil surface CO_2 flux was measured weekly during the growing season (May 2–August 5) and biweekly from October 14 until the ground froze (after November 23). Measurements were not made between August 5 and October 14 due to instrument failure. All measurements were taken between 9 and 12 a.m. of the same day to reduce variability in CO_2 flux due to diurnal changes in temperature (Parkin and Kaspar, 2003). The CO_2 flux was measured at a randomly selected point within each plot using an Environmental Gas Monitor chamber attached to a data logger (Model No. EGM-4, PP System, Haverhill, MA). The chamber was 15 cm in height, 10 cm in diameter, and had the capacity to measure CO_2 flux from 0 to 9.99 g CO_2-C m^{-2} h^{-1}. The chamber was placed on the soil surface for 2 min in each plot until the CO_2 flux measurement was recorded in the data logger (Sainju et al., 2006). Soil temperature and moisture content measurements were obtained along with each soil CO_2 flux measurement. The soil temperature near the chamber was measured from a depth of 0–15 cm using a probe attached to the data logger. Daily average air temperature and total rainfall during the study period were collected from a meteorological station located at 0.8 km from the study site (Sainju et al., 2006).

2.3. Measurements of soil physical characteristics

Soil physical characteristics measured at the site included soil bulk density, moisture content and particle size distribution. Soil bulk density and moisture content were measured by collecting undisturbed soil cores from 0 to 10 and 10 to 20 depths using a 50 mm diameter probe. Soil moisture content was measured using a gravimetric method.

Particle size distribution for each core was determined by the hydrometer method. Each measurement for each soil property was replicated three times. The amount of sand, silt, and clay in the soil at 0–20 cm depth ranged from 640 to 674, 176 to 18.4, and 150 to 16.6 g kg^{-1}, respectively. Soil bulk density at 0–10 cm depth ranged from 1.5 to 1.58, 1.49 to 1.59, 1.57 to 1.65 and at 10–20 cm depth the bulk density ranged from 1.60 to 1.68, 1.65 to 1.73, and 1.63 to 1.71 Mg m^{-3}, for NT, CT, and UGA, respectively.

The total soil porosity was calculated from measured bulk density data and a soil particle density of 2.65 g cm^{-3}. Soil air-filled porosity was calculated by subtracting the volumetric water content from the soil total porosity.

2.4. Statistical analyses

Soil CO_2 flux, soil temperature, soil moisture content and air-filled porosity parameters were analyzed using the analysis of repeated measures procedure in the MIXED model of SAS (SAS Institute, 2003). The ANOVA was used in accordance with the experimental design to ascertain the effects of irrigation and tillage on soil CO_2 flux and soil properties. Irrigation was considered as the main plot, treatment as the split plot, and date of measurement as the repeated measure treatment for analysis of data. The relationships between soil CO_2 flux, soil temperature, soil moisture content and air-filled porosity were analyzed using regression analysis. Regression analysis was used to determine the relationship between the CO_2 flux rate and soil properties. A stepwise multiple linear regression procedure was used to determine the effect or relative importance of each soil property on soil surface CO_2 flux. All statistical analyses were performed using SAS software procedures.

3. Results and discussion

3.1. Irrigation

The effects of the irrigation on soil surface CO_2 flux, soil temperature, and soil moisture content are shown in Fig. 1a–c, respectively. Soil surface CO_2 evolution was significantly affected by irrigation at the 0.1 probability level over the course of the study. Although temporal variations in CO_2 fluxes between irrigated and non-irrigated treatments existed, these variations were not significant at the 0.05 probability level (Fig. 1a; Table 1). This could be attributed to sufficient amounts of rainfall during May, June, and July, which explains smaller differences in soil surface CO_2 fluxes between irrigated and non-irrigated plots (Fig. 1a). Soil surface CO_2 fluxes increased after each precipitation or irrigation event and decreased abruptly in dry periods in both irrigated and non-irrigated plots (Fig. 1a).

Soil CO_2 fluxes were slightly higher in irrigated plots than in non-irrigated treatments in July and August. The increase in CO_2 emission in irrigated plots during these 2 months is attributed to an increase in soil moisture content due to five irrigation events (one application per day as follows: June 7 and 14, 13 mm each day; July 7 and 11, 25.4 mm each day; and July 14, 10.2 mm) (Fig. 1a). Noticeably higher moisture contents, higher CO_2 fluxes and lower soil temperature levels in irrigated plots were observed, as expected; all were due to irrigation applications (Fig. 1).

The peak soil moisture levels for both irrigated and non-irrigated treatments occurred in May, the first week of June and mid-July after the area received large amounts of rainfall; there was no precipitation at the end of June or the beginning of July. Despite small variations in soil moisture levels between irrigated and non-irrigated treatments in some months, measured soil moisture was significantly different between irrigated and non-irrigated treatments at a 0.1 probability level (Fig. 1c; Table 1).

Furthermore, measured soil temperatures were significantly different between irrigated and non-irrigated treatments (Fig. 1b; Table 1). Soil temperature in both treatments increased rapidly in May and June, peaked in July and August and gradually declined through October and November. The average difference in soil temperature between irrigated and non-irrigated plots across all sampling dates was approximately 1 °C. The cooler temperature in irrigated plots could be related in part to higher soil moisture levels and evaporation from the soil surface (Sainju et al., 2006).

Based on this study, irrigation also resulted in an increase of annual CO_2 emission from the soil surface in irrigated plots by more than 7 Mg CO_2 ha^{-1} yr^{-1} compared to non-irrigated plots.

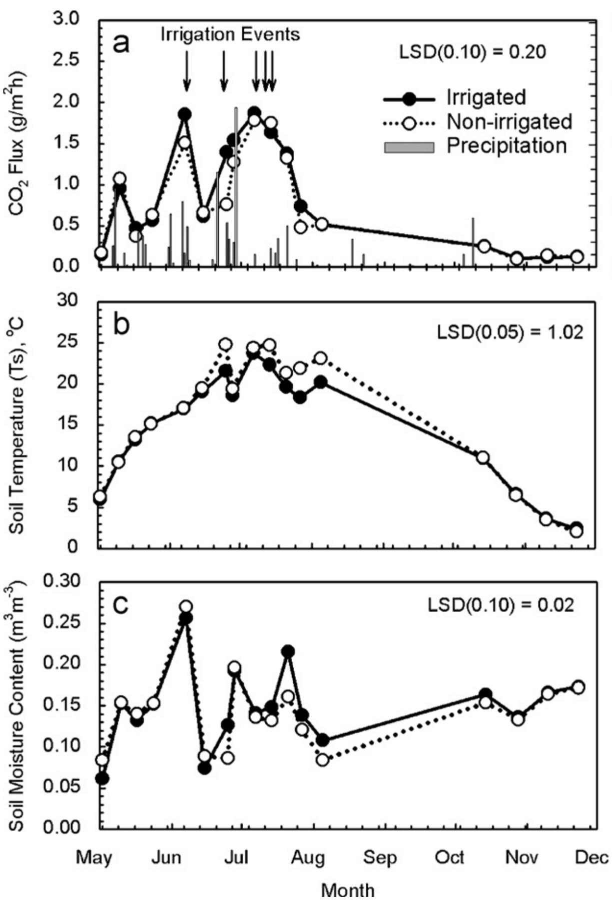

Fig. 1. Measurements of (a) soil CO_2 flux rates, (b) soil temperature, and (c) moisture content for irrigated and non-irrigated plots. Arrows in (a) indicate five irrigation events (one application per day as follows: June 7 and 14, 13 mm each day; July 7 and 11, 25.4 mm each day; and July 14, 10.2 mm).

3.2. Soil temperature

Soil temperature has a marked effect on CO_2 evolution from the soil surface. The parallel patterns in Fig. 1a and b indicate that soil CO_2 emission fluxes increased with soil temperature.

Non-linear regression analysis was used to model the influence of soil temperature on soil CO_2 flux rates. The CO_2 flux rates increased as a function of soil temperature; the relationship between soil temperature and CO_2 flux from the soil surface was significant and well described by exponential functions for both irrigated and non-irrigated, combined, and tillage treatments (Figs. 2 and 3). These

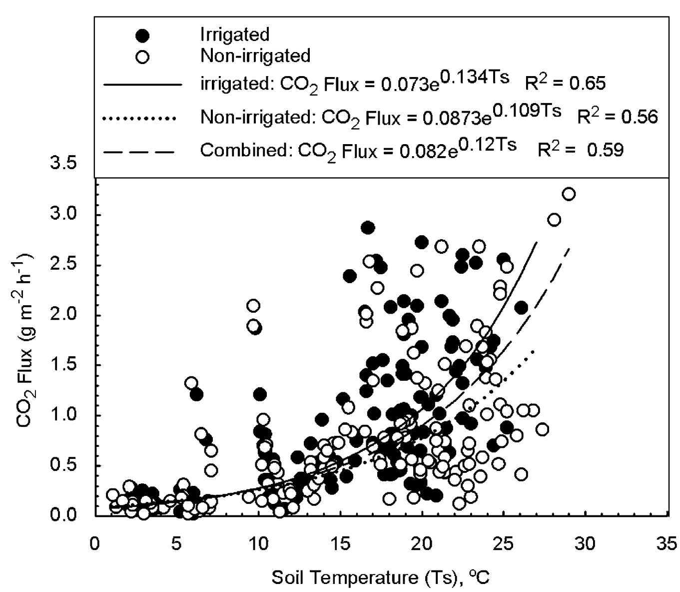

Fig. 2. Exponential relationships between soil surface CO_2 flux and soil temperature for irrigated and non-irrigated and both combined.

Table 1
Effect of irrigation and tillage system on soil surface CO_2 flux and soil properties

Irrigation	Tillage	CO_2 flux ($g\,m^{-2}\,h^{-1}$)	Soil temperature (°C)	Soil water content ($m^3\,m^{-3}$)	Air-filled porosity ($m^3\,m^{-3}$)
Irrigated		0.8404[a††]	14.6[a†]	0.149[a††]	0.256
Non-irrigated		0.7592[b]	15.6[b]	0.140[b]	0.260
	NT	0.6842[b]	15.0[a]	0.148[a]	0.255[a]
	CT	1.0426[a]	15.1[a]	0.144[a]	0.268[a]
	UGA	0.6726[b]	15.3[a]	0.141[a]	0.250[a]

[†]Different letters indicate significantly different values at $P<0.05$.
[††]Different letters indicate significantly different value at $P<0.1$.

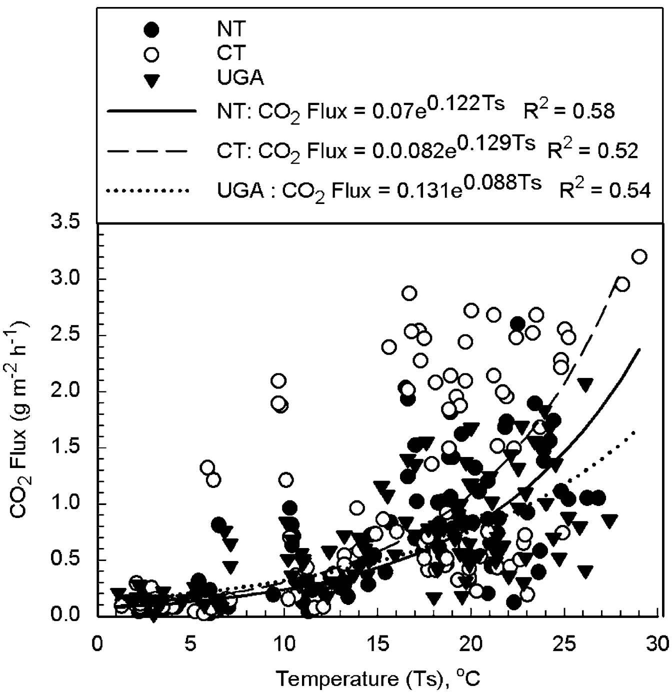

Fig. 3. Exponential relationships between soil surface CO_2 flux and soil temperature for NT, CT, and UGA treatments.

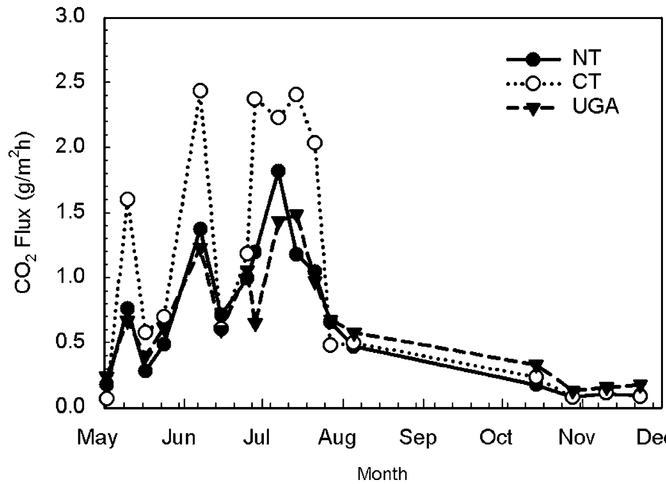

Fig. 4. Temporal variations of CO_2 flux as affected by tillage.

exponential functions indicated that CO_2 flux was significantly correlated with soil temperature for all irrigation and tillage treatments (Figs. 2 and 3). The exponential models based on soil temperature account for 65%, 56%, and 59% of the variation in CO_2 fluxes for irrigated, non-irrigated, and combined data, respectively (Fig. 2). The results of this study are similar to those of previous studies of CO_2 flux. Davidson et al. (1998), Maag and Vinther (1999), Bajracharya et al. (2000), and others who reported strong relationships between CO_2 flux and soil temperature and indicated that the rates of CO_2 evolution increased exponentially with increases in soil temperature. However, Savage and Davidson (2003) reported a linear relationship ($R^2 = 0.35$) between soil CO_2 flux and soil temperature at a depth of 4.5 cm.

As previously discussed, lower soil temperature and higher moisture content were observed with irrigated treatments (Fig. 1). Soil CO_2 fluxes were slightly higher in irrigated plots than in non-irrigated treatments in July and August. Increased soil moisture content rather than a difference in soil temperature probably increased CO_2 flux with irrigation. Increased CO_2 fluxes after irrigation resulting from increased C mineralization and root respiration have been observed (Curtin et al., 2000). Noticeably higher moisture contents, higher CO_2 fluxes and lower soil temperature levels in irrigated plots were observed, as expected; all were due to irrigation applications (Fig. 1).

On the other hand, tillage had no significant effect on soil temperature or soil moisture content (Table 1). Despite this, higher soil CO_2 fluxes were observed from CT followed by NT and UGA treatments (Table 1; Fig. 4). Increased soil water content and decreased soil temperature in NT compared with conventional till have been reported (Curtin et al., 2000; Al-Kaisi and Yin, 2005).

3.3. Soil tillage

Significant differences in soil surface CO_2 flux rates were observed between CT and both NT and UGA treatments ($P<0.05$); however, no significant differences were observed between NT and UGA treatments over the course of the study. The mean fluxes were lower under NT and UGA treatments compared to CT treatment (Table 1).

The highest soil CO_2 fluxes were observed from CT, followed by NT and UGA treatments (Table 1; Fig. 4). More CO_2 emissions were produced from tilled soils than from no-tillage or undisturbed soil. Tillage and soil disturbance strongly affect CO_2 emission by creating soil conditions favorable for oxidation and mineralization of organic C in the soil. A NT system or undisturbed soils, on the other hand, are less dissipative and produce lower levels of CO_2 fluxes. The UGA treatment showed the lowest CO_2 emission fluxes. The plant residues decomposed more slowly when they were left on the soil surface during the NT and UGA treatments than when they were incorporated; this is likely the reason for lower CO_2 emission fluxes from the NT and UGA treatments than from the CT treatment (Ball et al., 1999; Curtin et al., 2000). The results of this study suggest that tillage intensity should be minimized in order to reduce CO_2 production and emission from the soil. Moreover, NT with surface residue can further decrease CO_2 emission compared to NT without surface residue (Al-Kaisi and Yin, 2005). In contrast, tillage intensity increases CO_2 emission by increasing aeration due to greater soil disturbance (Roberts and Chan, 1990).

Where possible, it is beneficial to select sustainable soil management practices such as reduced tillage and irrigation

Table 2
Linear regression models for explaining variation in soil surface CO_2 flux ($g\,m^{-2}\,h^{-1}$) using soil moisture content and air-filled porosity

Soil variable	Treatment	Equation	R^2	*P*-value	Standard error
Moisture content, θ_v	NT	CO_2 flux $= 0.28+2.76\theta_v$	0.08	0.0058	0.54
	CT	CO_2 flux $= -0.14+7.99\theta_v$	0.20	<0.0001	0.85
	UGA	CO_2 flux $= 0.41+1.90\theta_v$	0.05	0.02	0.47
	Combined	CO_2 flux $= 0.19+4.17\theta_v$	0.11	<0.0001	0.67
Air-filled porosity, ε	NT	CO_2 flux $= 1.17-1.89\varepsilon$	0.06	0.0183	0.55
	CT	CO_2 flux $= 2.12-4.06\varepsilon$	0.11	0.0007	0.90
	UGA	CO_2 flux $= 0.98-1.18\varepsilon$	0.03	0.126	0.47
	Combined	CO_2 flux $= 1.42-2.40\varepsilon$	0.06	<0.0001	0.69

to increase carbon sequestration, improve soil quality and help minimize CO_2 emission from the surface soil of agricultural land, thereby protecting the environment from global warming.

The ANOVA results showed that the interaction between irrigation and tillage treatments was not significant for CO_2 emission fluxes, soil temperature, moisture content, and air-filled porosity.

3.4. Soil moisture

Soil moisture content is another important factor affecting biological respiration and soil CO_2 evolution. The relationship between soil CO_2 emission fluxes and both volumetric soil moisture content and air-filled porosity can be clearly demonstrated by plotting both soil variables against soil CO_2 flux (not shown). A direct linear relationship was found between volumetric soil moisture content and CO_2 flux (Table 2). This can be attributed to the fact that sufficient soil moisture content stimulates microbial activity and enhances root respiration, thereby increasing CO_2 emission from the soil surface.

In contrast, low moisture conditions affect roots and microbial respiration adversely; Orchard and Cook (1983) found a decrease in microbial respiration when the soil matric potential fell below -0.01 MPa, which they attributed to a decline in bacterial activity.

Soil CO_2 emission increases with increasing soil moisture content to an optimal level. This increase in CO_2 fluxes was more pronounced in the CT than in either the NT or UGA treatments under the same soil moisture level. At drier soil conditions, small or no differences in CO_2 emission were detected among the three treatments (Table 2).

3.5. Air-filled porosity

The effect of soil air-filled porosity and tillage on CO_2 evolution presented a scenario opposite that of soil moisture content. Because soil air-filled porosity is inversely proportional to the volumetric moisture content, an inverse relationship and negative correlation was found between air-filled porosity and CO_2 flux from the soil surface (Table 2). According to Ball et al. (1999), low or zero CO_2 fluxes under NT are associated with reduced air-filled porosity and gas diffusivity. Based on results of this study, remarkable differences in CO_2 fluxes were found between CT and both NT and UGA at low air-filled porosity. These differences became smaller as air-filled porosity increased and the differences diminished at approximately 40% of air-filled porosity (Table 2).

3.6. Relationships between CO_2 flux and soil properties

A stepwise regression procedure was used to select the significant variables that were included in the individual regression model. A significant multiple regression equation (Eq. (1)) was developed between CO_2 flux and volumetric moisture content (θ_v) and soil temperature (T_s):

$$CO_2\ \text{flux} = e^{-3.477+0.123T_s+6.381\theta_v}, \quad R^2 = 0.68, \quad P \leqslant 0.01 \tag{1}$$

Not surprisingly, soil temperature was the major driving factor in the equation that considerably influenced the soil CO_2 flux rate, followed by the soil moisture content. Using stepwise regression results, soil temperature and soil moisture content accounted for 59% and 9% of the variability in CO_2 flux, respectively. However, the air-filled porosity accounted for less than 1%; thus, it was not included in the model. Under field conditions, the soil CO_2 flux rate could be a function of soil temperature and moisture content due to changes in soil, water and land management practices.

The significant relationship between CO_2 flux and soil temperature is well known (Bajracharya et al., 2000; Parkin and Kaspar, 2003). High CO_2 flux usually occurs in the summer when soil temperature is higher and soil moisture content and substrate C availability are adequate, while low CO_2 emission occurs in the winter when soil biological activity is minimal due to near-freezing soil conditions (Bajracharya et al., 2000). Savage and Davidson (2003) developed an exponential function that combined both soil temperature and moisture content with soil respiration. Their equation accounted for 65% of the variation in soil respiration throughout the summer season (June–August). However, the soil temperature alone in their equation accounted for only 35% of the variation during the summer sampling season. Thus, there is ample evidence showing the influence of temperature on CO_2 emission, yet this does not minimize the importance of soil moisture which could conceivably be the driving factor under different circumstances than were present in our study.

4. Conclusions

Irrigation increased carbon dioxide (CO_2) emission from the soil surface to the atmosphere and therefore reduces the amount of C sequestered by the soil. Furthermore, increasing soil temperature was accompanied by increasing soil CO_2 fluxes. A positive, high correlation was found between soil temperature and the CO_2 emission from the soil surface, which was well described by an exponential function.

Conventional tillage of malt barley leads to higher levels of CO_2 fluxes that were significantly different from both no-till (NT) malt barley and undisturbed grass-alfalfa (UGA) treatments. However, there were no significant differences with respect to soil CO_2 emission between NT and UGA treatments.

The results suggest that adopting less intensive tillage such as NT or strip tillage will prove remarkably effective in reducing soil CO_2 evolution from land being converted from perennial forages to annual crops. Furthermore, since irrigation increases CO_2 emission, we conclude that careful irrigation management will help minimize the loss of C to the atmosphere while maintaining sustainable crop production levels in transitional lands.

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