Impacts of Wet–Dry Cycles and a Range of Constant Water Contents on Carbon Mineralization in Soils under Three Cropping Treatments

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Soil water content and cropping history play important roles in soil organic carbon inputs, decomposition, and nutrient cycling. However, variations in soil water content including wetting and drying events can influence organic carbon transformations in soils. The impacts of constant soil water contents (30, 45, 60, 75, and 90% water-filled pore space, WFPS), wet–dry (W–D) cycles (five 10-d cycles varying between 90 and 30% WFPS) and cropping treatments on carbon mineralization (CO_2 emissions) and dissolved organic carbon (DOC) were investigated using repacked cores of a clay loam soil incubated for 50 d. The cropping treatments included monoculture corn (*Zea mays* L.), a 2-yr corn–soybean (*Glycine max* L. Merr.) rotation (C–S), and a 3-yr corn–soybean–winter wheat (*Triticum aestivum* L.) rotation (C–S–WW) as these were believed to impact the carbon status of the soils. The carbon mineralization rates increased with increasing soil water content, and generally achieved the highest rates after 10 d. Cumulative carbon mineralization was greatest with the wettest constant soil water content treatment (i.e., 90% WFPS) and decreased with decreasing constant WFPS values. The average water content over the 10 d drying process for the W–D treatment was 63% WFPS. Cumulative carbon mineralization during the W–D cycles was similar to that for the constant 60% WFPS treatment. The corn phase of the C–S–WW rotation produced lower carbon mineralization rates than the corn phase of the C–S rotation and monoculture corn for each constant soil water content treatment. The DOC levels dramatically decreased over the first 10 d and then remained between 36.5 and 69.8 mg C kg^{-1} for the subsequent 40 d. Cropping treatments did not significantly affect the DOC levels. In general, the effect of the W–D cycles on carbon mineralization appeared to be related more to the average soil water content during the drying process than to soil carbon release as a result of soil drying and rewetting.

Abbreviations: C–S, corn–soybean rotation; C–S–WW, corn–soybean–winter wheat rotation; DOC, dissolved organic carbon; SOC, soil organic carbon; W–D, wetting–drying; WFPS, water-filled pore space.

Surface soils often undergo rapid wetting followed by drying periods as a result of precipitation or irrigation. Wetting and drying are important processes in soil as they influence aggregation, soil organic matter decomposition, and nutrient cycling. These fluctuations in near-surface soil water content are expected to be even greater in the future due to more frequent extreme weather events resulting from climate change (IPCC, 2007). Numerous studies have shown that the rapid wetting of a dry soil can generate a large CO_2 "flush" ('Birch effect') that can continue for up to several days (Birch, 1958; Clein and Schimel, 1994; Franzluebbers et al., 2000; Fierer and Schimel, 2002). Carbon dioxide emissions from rewetted soils are often elevated by as much as 500% compared with soils under constant water content, and the elevated CO_2 emissions generally persist for 2 to 6 d following the rewetting event (Fierer and Schimel, 2003). The diffusion of soluble substrates (e.g., nitrate) is reduced at lower soil water contents, while

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the diffusion of oxygen is constrained at higher soil moisture, which both limit soil microbial respiration (Skopp et al., 1990, Drury et al., 1992). Generally, CO_2 emissions increase with soil water content until about 85% water-filled pore space (WFPS) and then decrease with higher soil water content (Zhang et al., 2004b; Rey et al., 2005).

Two mechanisms are apparently responsible for producing the flush of CO_2 on soil rewetting. One is microbial respiration of nonbiomass soil organic matter rendered accessible when aggregates are disrupted during the W–D cycles (Appel, 1998; Denef et al., 2001). The other is microbial respiration of microbial biomass carbon liberated by cell lysis and osmotic shock during the drying phase (Kieft et al., 1987; Halverson et al., 2000). Hence, both biomass and nonbiomass carbon contribute to the CO_2 pulse on soil rewetting (Fierer and Schimel, 2003; Scheu and Parkinson, 1994). Xiang et al. (2008) found that "drying and rewetting led to a cascade of responses (soluble carbon release, biomass growth, and enhanced microbial activity)" that affected previously unavailable soil carbon. Many factors can influence carbon mineralization in W–D events, such as the frequency of W–D cycles (Fierer and Schimel, 2002), the depth of soils (Xiang et al., 2008), and soil compaction (Beare et al., 2009). Nevertheless, the 'Birch effect' of W–D cycles on carbon mineralization is not always observed (Kruse et al., 2004; Muhr et al., 2008).

Several studies have reported that W–D cycles stimulated carbon mineralization (Priemé and Christensen, 2001; Fierer and Schimel, 2002, 2003; Xiang et al., 2008) whereas other studies showed no change or a decrease in cumulative carbon mineralization relative to a moist control soil (Mikha et al., 2005; Magid et al., 1999). Xiang et al. (2008) found that microbial activity in surface soils was either moderately stimulated or not affected by multiple W–D cycles whereas activity was increased by up to eightfold in subsurface soils. Mikha et al. (2005), on the other hand, reported that multiple W–D cycles were found to reduce the cumulative carbon mineralization relative to a treatment which was maintained at a constant water content. Borken and Matzner (2009) indicated in a recent review paper that carbon mineralization is related to the intensity and duration of drying as well as other factors including the quantity and distribution of precipitation, temperature, etc. They also commented that in many laboratory studies the mineralization rates during W–D cycles may have been compared to constant water content controls that were not at the ideal soil water content for maximum carbon mineralization. Hence the relative increase in CO_2 production resulting from a W–D event may be substantially smaller if the control was incubated at ideal soil water content. Furthermore, we are not aware of incubation studies where carbon mineralization during W–D cycles is compared to mineralization under a range of constant moisture contents.

Dissolved organic carbon is an actively cycled soil carbon pool and DOC level has been proposed as an indicator of the carbon availability to soil microorganisms. The DOC is a precursor of microbial growth and activity, thus driving decomposition processes in the soil (Boyer and Groffman, 1996). Soil water content and W–D cycles affect decomposition rates of soil organic carbon (SOC) (Hogg et al., 1992; Fierer and Schimel, 2002; Zhang et al., 2004b; Chow et al., 2006) and the quantity as well as the chemical characteristics of DOC (Blodau et al., 2004; Chow et al., 2003; Christ and David, 1996). Under constant water content, DOC production increases with the soil water content (Christ and David, 1996). The W–D cycles increase DOC concentration on soil aggregate surfaces through a depletion of DOC in the aggregate interior (Zhang et al., 2004a). Although W–D cycles have been shown to increase DOC concentrations (Lundquist et al., 1999), DOC is not generally considered to be an important source of the carbon mineralized following rewetting of dry soil (Fierer and Schimel, 2003). Some studies reported that W–D events did not increase the decomposition of native soil organic material or production of DOC (Chow et al., 2006; Magid et al., 1999).

Crop inputs and the quality and bioavailability of soil organic carbon influence soil physical properties such as aggregation and wettability, which in turn affect the dynamics of carbon mineralization in soils (Lamparter et al., 2009). Land use effects on soil DOC are partly determined by the amount and type of carbon input (Campbell et al., 1999a 1999b; Zsolnay, 1996). Soon et al. (2007) found that crop rotations influenced both the light fraction carbon and carbon mineralization. Drury et al. (2008) observed that CO_2 emissions varied as a function of cropping history and the differences observed were dependent on whether the crop was grown as a monoculture or as part of a crop rotation. Including legume crops in the rotation increased DOC in the soil compared to cropping to gramineae species (Chantigny et al., 1997; Campbell et al., 1999a).

Therefore, in this study we evaluated the influence of W–D cycles with a series of control treatments held at constant water contents. These treatments were chosen to examine the combined influence of soil water contents (constant vs. W–D cycles) and cropping history (monoculture corn vs. corn in a 2- or 3-yr rotation) on carbon mineralization. This is a companion paper to one published on the effects of constant and fluctuating water contents on N_2O emissions from soils (Guo et al., 2010).

MATERIALS AND METHODS

Field Site and Soil Collection

This study uses a long-term crop rotation experiment which was established in the fall of 2001 at Woodslee, ON, Canada (42°13′ N, 82°44′ W) and includes 17 cropping treatments. The average annual air temperature and precipitation at the field site are 8.9°C and 832 mm, respectively. The soil is a Brookston clay loam (fine-loamy, mixed, superactive, mesic Typic Argiaquoll, in the USDA Soil Taxonomy System, or Orthic Humic Gleysol in the Canadian Soil Classification System), containing 28% sand, 35% silt, and 37% clay in the Ap horizon. Agronomic information on the full rotation experiment is described by Drury et al. (2008). In this study, composited surface soil (0–10 cm) was collected on 14 Apr. 2008 before spring secondary

Table 1. Selected chemical properties of the soils used in this study (0–10-cm depth).

Cropping system	pH (H_2O)	Total C	Total N	DOC†	NO_3^-–N	NH_4^+–N
		g C kg^{-1}	g N kg^{-1}	mg C kg^{-1}	mg N kg^{-1}	
Monoculture corn	6.2 (0.02)a‡§	23.2 (0.07)a	2.02 (0.02)a	275 (1.70)a	4.46 (0.13)a	3.90 (0.13)a
C–S rotation corn	6.5 (<0.01)a	23.5 (0.04)a	2.06 (0.03)a	235 (2.08)b	3.60 (0.04)b	2.82 (0.01)b
C–S–WW rotation corn	6.7 (<0.01)a	24.1 (0.29)a	2.11 (0.02)a	235 (1.84)b	3.84 (0.13)b	2.91 (0.02)b

† DOC: dissolved organic carbon.

‡ Values in parenthesis are the standard error of the mean (n = 4).

§ Means within a column followed by the same letter are not significantly different ($p < 0.05$).

tillage, from three cropping treatments, including monoculture corn (*Zea mays* L.), a 2-yr corn–soybean (*Glycine max* L. Merr.) rotation (C–S) and a 3-yr corn–soybean–winter wheat (*Triticum aestivum* L.) rotation (C–S–WW). In all treatments, the previous crop was corn (2007) and the previous tillage was fall chisel plow (2007). The spring sampling period was chosen as we were interested in simulating the impacts of fluctuating water contents during the growing season and cropping history on changes in carbon mineralization and DOC. The field-moist soil samples were sieved through a 4-mm sieve and visible roots and stones were carefully removed by hand. The sieved samples were then air dried to bring all of the samples to a similar initial water content, and stored in double-zipped polyethylene bags in the dark at 4°C to maximize sample stability during storage before the incubation experiments. Some selected physical and chemical properties of the soils are shown in Table 1.

Incubation Experiment and Gas Sampling

As the experimental protocol involving N_2O emissions and W–D cycles is described in detail by Guo et al. (2010), only the aspects relevant to CO_2 emissions will be described here. Water-filled pore space is defined as the percentage of the total soil pore volume occupied by water. In this study, soil samples from the three cropping systems were incubated over 50 d using five constant WFPS scenarios (30, 45, 60, 75, and 90% WFPS), and one fluctuating WFPS scenario (W–D), each with four replicates (n = 4). In the W–D scenario, five major W–D cycles were conducted over the 50 d incubation which is consistent with growing season observations at the field site (Drury et al., 2006; 2008). At the start of each W–D cycle, the soil was "instantly" wetted to 90% WFPS, then allowed to dry by evaporation to 30% WFPS over a 10 d period, to produce a saw-tooth pattern (Fig. 1).

A total of 360 soil cores were prepared by weighing and packing soil (57.0 g, dry weight basis) into an aluminum ring (4.8 cm diam. and 2.5 cm height) to achieve a bulk density of 1.26 Mg m^{-3} (similar to the density measured in the field at the experimental site). A cheese cloth was affixed to the bottom of each core with an elastic band to retain the soil.

At the beginning of the experiment, water was added to the soil cores as evenly as possible using a pipette to bring the water contents to 20% below their target WFPS and then the soil cores were pre-incubated for 5 d at 25 ± 1°C and 50% relative humidity to establish microbial activity. After pre-incubation, a potassium nitrate solution (50 mg NO_3^-–N kg^{-1} soil) was added to the soils to simulate N fertilizer addition at planting and to produce the target WFPS. Each prepared soil core was then placed inside a 250 cm^3 mason jar. The jars with the constant WFPS treatments were covered with parafilm with four pin holes to maintain an aerobic environment, while minimizing water loss. The W–D treatment jars were covered with parafilm with eight holes which were made with a paper hole punch (0.65 cm diam.) so that 10% of the parafilm was open to the atmosphere. These holes allowed the cores to dry by evaporation from 90% WFPS to 30% WFPS in 10 d. Samples were incubated for 50 d in a controlled environmental chamber at 25 ± 1°C and 50% relative humidity using a completely randomized design. Distilled water was carefully and evenly added to the soils by pipette in the W–D treatment at the start of each W–D cycle to produce 90% WFPS (Fig. 1). The WFPS in the W–D treatments was determined by weighing the soil cores at the same time as gas sample collection (see below). The constant WFPS treatments were maintained at their target WFPS values by weighing the soil cores every day and adding distilled water as needed. Carbon dioxide emission rate in each mason jar was measured over five 10-d cycles on Days 1, 2, 4, 6, 8, and 10 within each cycle (Fig. 1 and 2). This was achieved by collecting gas samples from the head-space above the soil using a protocol similar to Drury et al. (2003).

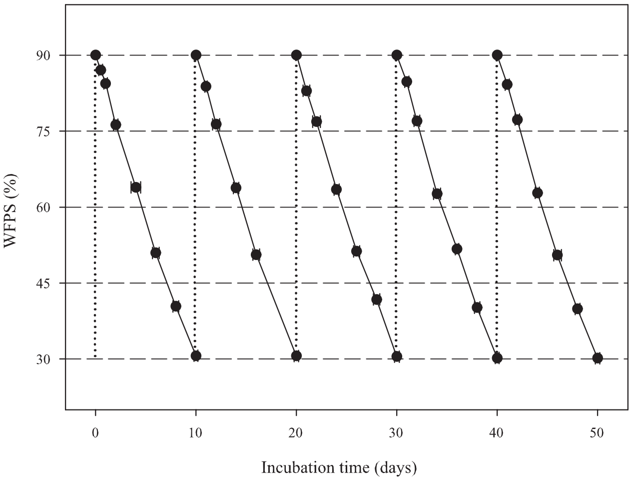

Fig. 1. Schematic diagram of the incubation process for the wetting–drying (W–D) cycles (solid lines) and constant water content (dashed lines) treatments. Each W–D cycle started by instantly wetting the soil to 90% water-filled pore space (WFPS) (vertical dotted lines) and then a 10-d dry-down period to 30% WFPS. The horizontal lines are the constant water content treatments (i.e., 30, 45, 60, 75, and 90% WFPS). Each point is the soil water content during drying when gas samples were collected. Bars are standard error (n = 12), error bars are not displayed in the some cases because the standard error was smaller than the symbol.

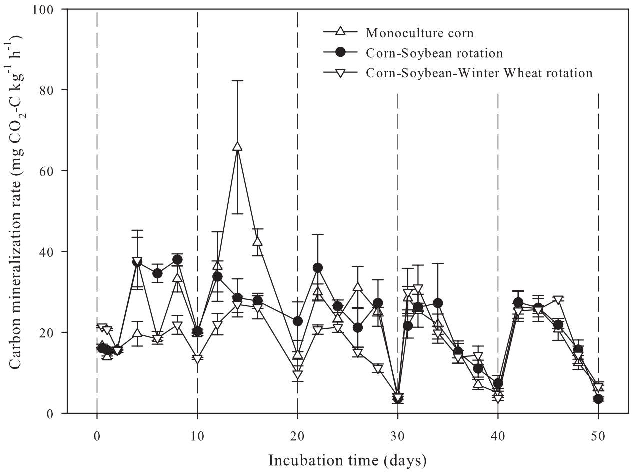

Fig. 2. Soil carbon mineralization rates over 50 d for the monoculture corn, corn phase of the corn–soybean rotation and the corn phase of the corn–soybean–winter wheat rotation for the five wet–dry cycles. Bars are standard error (n = 4).

Gas and Soil Analysis

The concentration of CO_2 in Exetainers was analyzed using a gas chromatograph (Varian 3800 GC, Mississauga, Canada) fitted with a Combi-PAL autosampler. The carbon mineralization rate was estimated as the increase of CO_2 concentration between 5 and 125 min. Cumulative carbon mineralization was calculated by integrating the measured data using Trapezoidal rule with linear interpolation between consecutive sampling dates.

Soil pH was measured in 1:2 soil–H_2O suspensions using a glass electrode. Total carbon and total N contents were determined using dry combustion (Leco CNS 2000, Leco Corp., St. Joseph, MI). Since the soil samples were carbonate free, total carbon content equaled soil organic carbon content. At the end of each 10 d cycle, a subset of four cores was removed and destructively sampled for DOC measurement. The DOC concentration was determined by extracting 10 g soil (dry weight basis) with 25 mL distilled-water and shaken for 30 min on a rotary shaker at 225 revolutions min^{-1}. Then the soil suspension was filtered through 0.45 μm mixed cellulose esters membrane (Fisher Scientific, PA) and the extracts analyzed using a Shimadzu TOC 5050C analyzer (Shimadzu, Japan). Concentrations of NO_3^-–N and NH_4^+–N were analyzed using the Berthelot reaction method for NH_4^+–N and the Cd reduction method for NO_3^-–N on a TRAACS 2000 (Bran + Luebbe Analyzing Technologies, Buffalo Grove, IL) autoanalyzer (Tel and Heseltine, 1990).

Statistical Analyses

Repeated measures two-way ANOVA was used to examine the main effects of soil water content and cropping system on carbon mineralization and DOC concentration. The GLM procedure was also used to compare the change in DOC between the initial and final stages of the incubation. A significance level of $p < 0.05$ was used unless otherwise indicated. Pearson's correlation coefficient (r) was used to describe the degree of correlation between variables. All statistical analyses were conducted using SAS 9.0 (SAS Institute, Cary, NC).

RESULTS

Overall Carbon Mineralization Rates

Overall carbon mineralization rates were determined by aggregating the CO_2 emission data for all three cropping treatments. Overall carbon mineralization rate was positively and significantly correlated with WFPS (r = 0.60 to 0.89, $p < 0.001$) for constant WFPS treatments (Table 2). Overall carbon mineralization for the W–D treatment was significantly correlated (r = 0.73 to 0.88, $p < 0.05$) with water content only during the 21–30, 31–40 and 41–50 d time periods (Table 2), which correspond with the third, fourth, and fifth drying phases, respectively (Fig. 1). The decrease in carbon mineralization rate during the drying process was very pronounced especially in the third, fourth, and fifth cycles (Fig. 2). It should also be noted that the highest carbon mineralization rates in the third to fifth cycle occurred about 1 to 2 d after the soils were rewetted, while there appeared to be more of a delay in reaching the maximum carbon mineralization in the first two cycles.

In the W–D treatments, overall carbon mineralization rates generally decreased with increasing number of W–D cycles (Fig. 2). In general, the C–S–WW rotation had lower carbon mineralization rates than monoculture corn or C–S during the first three cycles (i.e., first 30 d) but had similar rates as the other two cropping treatments in the last two cycles (Fig. 2). The monoculture corn treatment had the highest average carbon mineralization rate (65.8 mg CO_2–C kg^{-1} d^{-1}) at Day 14 (Fig. 2).

In all three treatments, cumulative carbon mineralization increased with the increase of WFPS in the constant WFPS treatments (Fig. 3). Cumulative carbon mineralization

Table 2. Correlation coefficients (r) between carbon mineralization rates and water-filled pore space (WFPS) for constant water contents, wetting–drying (W–D) cycles, and dissolved organic carbon (DOC).

Correlated variables	Incubation time, d				
	0–10	11–20	21–30	31–40	41–50
Carbon mineralization rate† vs. WFPS for the constant water contents treatments	0.60***	0.75***	0.74***	0.89***	0.75***
Carbon mineralization rate vs. WFPS for the W–D cycles‡	–0.33	0.50	0.73**	0.88***	0.88***
Carbon mineralization rate vs. DOC§	0.10	0.21	0.41	0.35	–0.31

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Carbon mineralization rate was determined using CO_2 emission rate from soil.

‡ The carbon mineralization rate at the point of gas sampling correlated with the soil water content at the same point in W–D cycle.

§ Constant WFPS and W–D cycle data aggregated.

among the three treatments at 30% WFPS varied from 495 to 562 mg CO_2–C kg^{-1} after 50 d. The cumulative carbon mineralization values for monoculture corn and C–S rotation were significantly higher ($p < 0.05$) after 50 d than that of the soil from C–S–WW rotation in the 45 to 90% WFPS range with the exception of the monoculture corn soil at 75% WFPS which had similar cumulative carbon mineralization (1380 mg CO_2–C kg^{-1}) as the C–S–WW treatment (1290 mg CO_2–C kg^{-1}) (Table 3). The highest cumulative carbon mineralization after 50 d was observed in the 90% WFPS treatment with 1550 mg CO_2–C kg^{-1} for both the monoculture corn and the corn phase of C–S rotation whereas the C–S–WW had a maximum of 1360 mg CO_2–C kg^{-1}.

In the W–D treatment, cumulative carbon mineralization was significantly greater ($p < 0.05$) in monoculture corn (1170 mg CO_2–C kg^{-1}) and C–S (1180 mg CO_2–C kg^{-1}) than in C–S–WW rotation (962 mg CO_2–C kg^{-1}) (Table 3). Cumulative carbon mineralization in the W–D treatment was also similar to that of the corresponding 60% WFPS treatments (Fig. 3). It should be noted that the time-weighted average WFPS during the drying process for the W–D treatment was 63% (Fig. 1). As shown in Fig. 4, the relationships between cumulative carbon mineralization at 50 d and constant WFPS followed strong linear regressions ($R^2 = 0.95$–0.99). In addition, substituting the time-weighted average WFPS from the W–D treatments (i.e., 63%) into these regressions produced cumulative carbon mineralization estimates that were similar to the corresponding measured values (Table 3, Fig. 4).

Statistical comparison of WFPS and cropping system showed that WFPS was the primary factor affecting carbon mineralization ($F = 23.5$–125, $p < 0.0001$) given that WFPS produced consistently higher F values than cropping treatment (Table 4). Significant interactions between WFPS and cropping treatment were observed for the 0- to 10- and 11- to 20-d periods.

The DOC values at the start of the incubations (i.e., 275, 235, and 235 mg C kg^{-1} for the soils from the corn phase of monoculture corn, C–S and C–S–WW, respectively, Table 1) were similar to those for field-moist soil at the time of sampling in November 2007 (i.e., 294, 337, and 283 mg C kg^{-1} for the soils from the corn phase of monoculture corn, C-S, and C-S-WW respectively), and this implies as a consequence that DOC was not affected appreciably by sample preparation and storage before the incubations (i.e., sieving, air-drying, storage at 4°C). The DOC values decreased significantly during the incubations with final concentrations ranging from 37.4 to 65.9 mg C kg^{-1}. There were no significant correlations between carbon mineralization

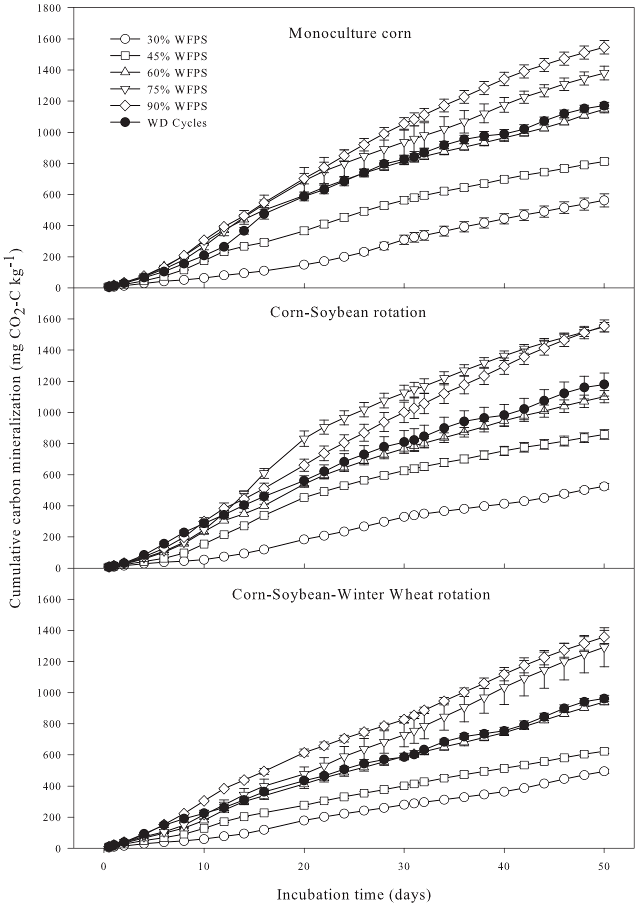

Fig. 3. Cumulative carbon mineralization over 50 d from monoculture corn, corn phase of the corn–soybean rotation and corn phase of the corn–soybean–winter wheat rotation at constant 30, 45, 60, 75, or 90% water-filled pore space (WFPS) treatments as well as for the five wet–dry cycles. Bars are standard error ($n = 4$).

Table 3. Cumulative carbon mineralization and dissolved organic carbon (DOC) after 50 d from the carbon phase of the soils under monoculture corn, a 2-yr corn–soybean (C–S) rotation and a 3-yr corn–soybean–winter wheat (C–S–WW) rotation treatments under varying soil moisture treatments.

Cropping system	30% WFPS†	45% WFPS	60% WFPS	75% WFPS	90% WFPS	W–D cycles
Cumulative carbon mineralization, mg CO_2–C kg^{-1}						
Monoculture corn	562 (42.3)‡Ea§¶	813 (18.2)Da	1150 (22.4)Ca	1380 (44.0)Bab	1550 (42.3)Aa	1170 (20.6)Ca
2-yr C–S rotation	525 (18.4)Da	857 (31.0)Ca	1100 (39.7)Ba	1550 (29.4)Aa	1550 (38.7)Aa	1180 (74.2)Ba
3-yr C–S–WW rotation	495 (14.0)Ca	624 (15.4)Cb	940 (18.9)Bb	1290 (125)Ab	1360 (42.1)Ab	962 (20.7)Bb
Dissolved organic carbon, mg C kg^{-1}						
Monoculture corn	55.5 (2.38)ABa	40.4 (3.13)Ca	40.0 (0.71)Ca	44.7 (3.13)BCb	46.7 (4.91)BCa	65.9 (4.28)Aa
2-yr C–S rotation	45.1 (1.39)Cb	38.3 (0.35)Da	41.8 (0.94)CDa	58.4 (1.99)Aa	52.3 (1.49)Ba	58.1 (1.11)Aab
3-yr C–S–WW rotation	49.5 (2.39)Aab	37.4 (0.96)Aa	44.4 (6.63)Aa	43.1 (0.88)Ab	43.3 (4.38)Aa	45.0 (2.52)Ab

† WFPS: water-filled pore space, W–D: wetting–drying.

‡ Values in parenthesis are the standard error of the mean ($n = 4$).

§ A–E: Means within a row followed by the same letter are not significantly different from each other ($p < 0.05$).

¶ a–b: Means within a column followed by the same letter are not significantly different from each other ($p < 0.05$).

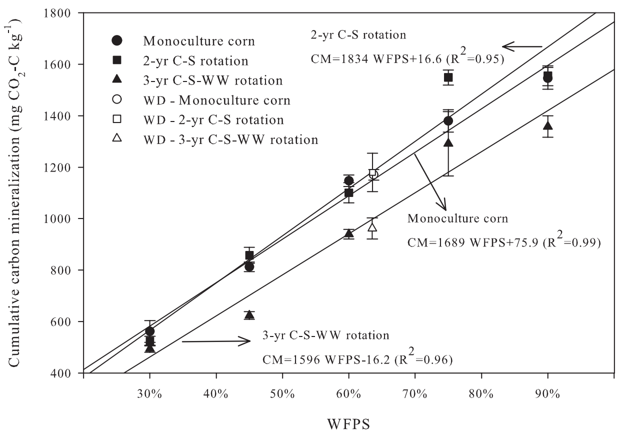

Fig. 4. The linear regressions between cumulative carbon mineralized (CM) after 50 d and water-filled pore space (WFPS) in the corn phase of soils from monoculture corn, corn–soybean rotation and corn–soybean–winter wheat rotation. Also included is cumulative carbon mineralized after 50 d for the wet–dry (W–D) cycles plotted against the time-weighted average WFPS for the W–D cycles.

rate and DOC concentration for the constant WFPS treatments over the five incubation periods (Table 2).

DISCUSSION

Strong positive relationships were found between carbon mineralization rates and WFPS, regardless of whether the soil had a constant water content or iterated through repeating drying cycles (Fig. 2, 3, and 4). Although some have found only weak relationships between mineralization rate and WFPS, or no relationship at all (Drewitt et al., 2002; Frank et al., 2002; Ruser et al., 2006), others observed relationships consistent with ours. For example, Zhang et al. (2004b) and Rey et al. (2005) found that CO_2 emissions increased with soil water content until about 85% WFPS which was similar to the maximum observed at 90% WFPS in this study, then decreasing emissions with higher soil water content. Linn and Doran (1984) found that the highest soil respiration rates occurred between 40 and 70% WFPS with lower rates above and below this range. The reduced soil respiration at low WFPS is likely due to restricted diffusion of available carbon to the microbial respiration sites and reduced respiration at high WFPS is probably the result of poor soil aeration and a consequent shift toward anaerobic microbes and/or processes (Skopp et al., 1990; Drury et al., 1992). The enhanced CO_2 production at high WFPS in this study might be partially attributed to improved diffusion of available carbon due to high soil water content. Another possibility is increased anaerobic respiration as supported by Guo et al. (2010). The carbon mineralization rates in the constant WFPS treatments except for the 30% WFPS declined with time (Fig. 2). Declining carbon mineralization rates suggest a concomitant decrease in carbon availability which may also be related to the steep decrease of DOC in the first 10 d. Carbon mineralization continued over the subsequent 35 to 40 d albeit at a generally declining rate, regardless of the soil water content and cropping system (Fig. 3).

Many studies have focused on the effect of drying and rewetting on carbon mineralization and microbial activity (e.g., Birch, 1958; Magid et al., 1999; Fierer and Schimel, 2002, 2003; Miller et al., 2005; Ruser et al., 2006; Butterly et al., 2009). Rewetting of dry soil can stimulate mineralization of SOC to produce an almost immediate pulse of CO_2 (Fierer and Schimel, 2002; Wu and Brookes, 2005). However, in this study, the increase of CO_2 flux in the first W–D cycle occurred a few days after the rewetting (Fig. 2). Despite an increase in CO_2 flux following rewetting of dry soil, the CO_2 pulse after wetting was not significantly higher than the carbon mineralization rates in the 75 and 90% WFPS treatments, which was consistent with the result of Muhr et al. (2008) which indicated that CO_2 fluxes quickly recovered back to control level (constant water content) after rewetting. The increase in carbon mineralization rate following rewetting of dry soil was partly related to the substrate released on microbial death and lyses and/or the rapid increase in microbial biomass and fungal hyphae or stress response of microorganisms (Magid et al., 1999). The increased exposure of organic residues following aggregate disruption could contribute to the observed increases in carbon mineralization (Denef et al., 2001). In this study, the soil water content in the W–D treatment at the end of drying was 30% WFPS which was higher than the air-dry WFPS value. Therefore, the rewetting process in this study might not result in as much osmotic shock and cell lyses as if the soil had been completely air dried at the end of each drying cycle. Note also near-surface field soils do not usually reach an air-dried state, especially in humid regions, due to capillary rise of subsurface water. In contrast, carbon mineralization has been observed to dramatically increase after rewetting a completely dry soil because soil organisms may also release osmoregulatory

Table 4. Summary statistics of a two-way ANOVA on the effects of soil moisture, cropping history, and wetting–drying (W–D) cycles on cumulative carbon mineralization.

		Incubation time, d											
Source	DF	0–10		11–20		21–30		31–40		41–50		Entire incubation	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
WFPS†	5	125.3	***	47.1	***	23.5	***	34.9	***	37.6	***	201.6	***
Cropping system	2	10.2	***	26.9	***	18.9	***	0.03	ns‡	4.94	*	29.4	***
WFPS × cropping system	10	4.69	***	6.26	***	1.42	ns	1.13	ns	1.88	ns	1.39	ns

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† WFPS: water-filled pore space.

‡ ns: not significant at 0.05 probability level.

substances to prevent cell lyses (Unger et al., 2010) and one-fourth to one-third of the resident biomass can be destroyed by an air-drying process (Bottner, 1985). Microbial activity was found to decrease in aerated soils with decreasing water content (Voroney, 2007). Most mineralization studies involving W–D cycles include only one constant water content. When Borken and Matzner (2009) reviewed the literature, they found that about 50% of the W–D studies found an increase in cumulative carbon mineralization, while the remainder showed no change or decrease in cumulative carbon mineralization, relative to a constant water content control. For example, Mikha et al. (2005) found that the cumulative carbon mineralization from repeated W–D cycles was lower than that obtained for a constant water content (24–26% gravimetric water content). In contrast, Miller et al. (2005) and Xiang et al. (2008) reported that W–D cycles stimulated cumulative carbon mineralization compared to two constant water content treatments (60% water-holding capacity and 28% gravimetric water content, respectively). By using a range of WFPS values (30, 45, 60, 75, 90% WFPS) as multiple controls in this study, we determined that carbon mineralization was primarily related to the average WFPS during the drying process (63% WFPS) as the carbon mineralization values for W–D cycles were similar to the values obtained with the soils incubated at 60% WFPS. Hence in this study, it does not appear that the wetting and drying process in the 90 to 30% WFPS range stimulated soil carbon mineralization. In contrast, the W–D cycles can cause very high nitrate removals but comparatively low N_2O emissions similar to those for low constant WFPS (Guo et al., 2010).

In a field study, Drury et al. (2008) observed that the CO_2 emission from the corn phase in a C–S–WW rotation was significantly higher than from monoculture corn and the corn phase of a C–S rotation. In this incubation study, however, the C–S–WW treatment produced the lowest cumulative carbon mineralization (Fig. 3). Several factors may be responsible for this discrepancy. For example, CO_2 respiration in the field includes soil carbon mineralization as well as plant root respiration. Further, the moisture contents, aeration status, and soil temperature in the field generally vary between cropping treatments as a result of differential evapotranspiration rates from different crop stages and cropping types. Moreover, Buyanovsky and Wagner (1986) estimated that the total annual input of carbon from corn residues was 2.5 and 2.7 times greater than from winter wheat and soybean, respectively. So from a carbon input perspective, the lower carbon mineralization rates for the C–S–WW incubation were not unexpected. Although the cumulative carbon mineralization was not significantly different between the monoculture corn and the C–S rotation, the soil from the C–S–WW rotation had the lowest cumulative carbon mineralization in all WFPS treatments (Fig. 3). Vyn et al. (2006) observed under field conditions that monoculture corn produced 14% greater CO_2 emissions than a C–S rotation because of the greater amounts of crop residue returned to the soil. Fierer and Schimel (2002) also reported differences in carbon mineralization rates following multiple wetting/drying events when soils were under different vegetation (i.e., oak vs. grass).

The higher DOC level in the soil under monoculture corn might be due to greater cumulative residue inputs over several years than with the 2-yr C–S or 3-yr C–S–WW rotation. In particular, soybean residues are comparatively low compared to corn and winter wheat and they tend to degrade very quickly. Although the DOC decreased steeply during the first 10 d in all treatments (data not presented), the DOC concentrations remained fairly stable in the subsequent 40 d of the incubation. Cook and Allan (1992a, 1992b) found that soil respiration rates declined during a 210-d incubation, but DOC amounts remained constant or increased. Gordon et al. (2008) and Lundquist et al. (1999) reported that W–D cycles led to an increase in DOC concentration. However, in this study it should be noted that the DOC concentrations in the W–D treatment were measured at the end of each 10 d drying cycle when the soil was driest. Prechtel et al. (2000) found that DOC fluxes in a forest surface soil were moderately affected by wetting and drying with an increase 3 to 5 d after rewetting followed by a decrease after 10 to 20 d of drying. Lundquist et al. (1999) explained that the effect of W–D cycles on DOC were due to: (i) a decrease in the microbial population that would reduce microbial utilization of the DOC, (ii) increased turnover of microbial biomass carbon and concentrations of microbial products, (iii) disruption of the soil structure. These processes may not have been as evident in this study as the soil was not completely air dried. Although the difference of DOC levels between the three soils was not as obvious as the cumulative carbon mineralization, the C–S–WW rotation generally had the lowest DOC levels among the soils (data not shown).

Although positive correlations between carbon mineralization rates and DOC concentrations in surface soil have been reported (Cook and Allan, 1992b; Lundquist et al., 1999; Chow et al., 2006), significant correlations did not occur in this study. In fact after an initial decline during the first 10 d of the incubations, DOC remained fairly stable which may imply that DOC formation and removal were at similar rates (Cook and Allan, 1992b; Lundquist et al., 1999; Chow et al., 2006).

CONCLUSIONS

Constant and varying WFPS as well as cropping history can significantly affect soil carbon mineralization. Cumulative carbon mineralization after 50 d increased linearly with increasing WFPS (Fig. 4). With the exception of the 30% WFPS treatment, CO_2 emission fluxes from the soil reached maximum values within 10 to 15 d. Maximum cumulative carbon mineralization after 50 d incubation occurred at 90% WFPS treatment (Fig. 3). The average WFPS in the W–D treatment was 63%, and the cumulative carbon mineralization after 50 d for W–D was similar to that of the 60% constant WFPS treatment, hence the W–D process did not appear to stimulate carbon mineralization after 50 d other than through its influence on the average WFPS during the incubation. In general, the cumulative organic carbon mineralization after 50 d from the C–S–WW rotation was significantly lower than the rates associated with monoculture corn and C–S rotation for each WFPS level. The cropping treatments did not impact DOC levels under different WFPS and W–D cycles. Unless DOC production and decomposition were at similar rates, it does not appear that DOC and CO_2 emissions were related after the first 10 d of incubation. Further studies are needed to investigate the extent and duration of soil drying on the CO_2 pulse following rewetting. The impacts of constant and varying soil water contents on soil-derived CO_2 emissions can be used to better predict the consequences of soil and water management and climate change on CO_2 emissions from agricultural ecosystems.

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