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Agriculture, Ecosystems and Environment 109 (2005) 75–86
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Soil carbon dioxide efflux from a claypan soil affected by surface compaction and applications of poultry litter

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Received 31 August 2004; received in revised form 18 January 2005; accepted 15 February 2005

Abstract

The effects of soil compaction on soil physical properties may alter soil microbial activities and processes, including carbon (C) cycling, and possibly affect agricultural production and environmental degradation. This study investigated the effects of surface soil compaction on soil C mineralization in a claypan soil amended with poultry litter (i.e. turkey excrement mixed with pine shavings as bedding). In a laboratory study, a Mexico silt loam soil was compacted to four bulk density levels (1.2, 1.4, 1.6 and 1.8 Mg m^{-3}) with and without poultry litter and incubated at 25 °C for 42 days. A field experiment with plots that were maintained fallow was also conducted in 2001 and 2002 on the same claypan soil in North Central Missouri. Soil was amended with litter (0 and 19 Mg ha^{-1}) and left uncompacted or uniformly compacted. Results showed that soil CO_2 efflux was decreased by compaction up to 72% in the laboratory study and 46% in the field study of 2002 ($P < 0.05$). Litter application enhanced soil CO_2 efflux ($P < 0.05$) due to the addition of readily available C from litter. In the laboratory study, soil CO_2 efflux was negatively correlated with soil bulk density and the proportion of micropores ($P < 0.05$). Conversely, soil CO_2 efflux was positively related with total porosity and the proportion of macropores ($P < 0.05$). In the field, surface soil compaction caused changes in soil water content and soil aeration, which may have had the greatest effect on variation in soil CO_2 efflux. These results indicate that both soil compaction and litter application change the rate of soil C mineralization, and the magnitude of those changes is modified by climatic variation.

Keywords: Compaction; Soil CO_2 efflux; Claypan soil; Litter

1. Introduction

Soil compaction is a major cause of reduced crop productivity in agroecosystems (Lee et al., 1996; Motavalli et al., 2003) and increases the potential for environmental degradation (Torbert and Wood, 1992; Soane and van Ouwerkerk, 1995). Compaction may

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doi:10.1016/j.agee.2005.02.013

adversely affect crop growth by increasing soil strength, which can restrict plant root development, decrease drainage and water movement in soils, and limit soil aeration. These conditions also promote nutrient losses that may consequently decrease crop growth and production. Soil compaction may also play a role in environmental pollution, such as promoting emissions of greenhouse gases, (Brussaard and van Faassen, 1994; Ball et al., 1999) and increasing water pollutants through higher volumes of surface runoff (Soane and van Ouwerkerk, 1995).

Soil compaction may also affect soil biological processes, including soil C mineralization (Brussaard and van Faassen, 1994; Jensen et al., 1996a, 1996b; De Neve and Hofman, 2000). Compaction increases soil bulk density and strength, compresses larger pores to smaller pores, decreases soil porosity, and restricts fluid and gas transport processes which all may affect soil biological processes. A decrease in macropore continuity in compacted soil may create less favorable conditions for soil microorganisms and microbial activity (Jensen et al., 1996b). Several studies have reported that soil microbial activity, assessed by monitoring changes in soil CO_2 efflux, was decreased with an observed increase of soil bulk density caused by compaction (Rochette et al., 1991; Torbert and Wood, 1992; Lee et al., 1996; De Neve and Hofman, 2000).

One method to remediate and reduce the effects of compaction is by application of organic materials (Reicosky, 2002). Soil organic matter reduces soil bulk density and increases cation exchange capacity, water holding capacity and infiltration rates. In addition, the presence of soil organic matter buffers changes in soil pH and soil temperature. Consequently, increases in soil organic matter positively affect soil microbial activity and may reduce rates of soil erosion (Nyakatawa et al., 2001). For example, several studies observed that manure-amended soils have increased soil microbial biomass, and rates of nutrient mineralization, and enzyme activity (Dick, 1997; Rochette et al., 2000; Bol et al., 2003; Parham et al., 2002). Adding bulky organic materials may also reduce the compactibility or compressibility of soils by increasing resistance to deformation and the elasticity of the soil (Soane, 1990; Larson et al., 1994). For example, a high rate of manure application (50 Mg ha^{-1}) reduced soil compactibility and increased the range in soil water content for trafficability (Mosaddeghi et al., 2000).

The severity of soil compaction can also be affected by soil morphology (Motavalli et al., 2003). For example, claypan soils, which are characterized by an abrupt and large increase in clay content in the subsoil compared to the overlying material, may be more severely compacted by field traffic and machinery than other soils because the subsoil claypan layer confines applied stresses to the soil surface horizon, causing additional surface soil compaction. Claypan soils are subject to seasonal excess water and root restrictions. The study of claypan soils is of interest because they comprise an area of about 4 million ha in the Midwestern USA (Jamison et al., 1968; Blanco-Canqui et al., 2002) and make up part of an additional 2.9 million km^2 of land resources globally which have seasonal excess water and minor root restricting layers (World Soil Resources, 2002).

While the effects of soil compaction on soil physical properties are well-documented, few studies have been conducted on the effects of surface soil compaction on soil biological properties, including effects on soil C mineralization of added organic amendments (De Neve and Hofman, 2000; Li et al., 2002). To improve both soil physical and organic matter management of claypan soils, more information is needed on the effects of soil compaction in this soil (Motavalli et al., 2003). In addition, knowledge of the effects of soil physical properties on soil CO_2 efflux may improve management practices for increased soil C sequestration and reduction of soil CO_2 emissions that may affect global warming. The objectives of this study were to: (1) investigate the effects of soil compaction and applied poultry litter on soil CO_2 efflux from a claypan soil and (2) determine the relationship between soil CO_2 efflux and soil physical properties under different soil bulk densities.

2. Materials and methods

2.1. Laboratory incubation study

The claypan soil used in the incubation study was a Mexico silt loam (U.S. Soil Taxonomy: fine, smectitic, mesic Aeric Vertic Epiaqualfs; FAO Soil Classification: Cutani-Stagnic Luvisols) from the Bradford Agronomy Center (38°53′N, 92°12′W) in North Central Missouri. A bulk sample was taken from the 0 to 10 cm depth, air-dried, ground and sieved (2-mm mesh). The particle size distribution of this soil was an average (±S.D.) of 59 ± 4 g kg^{-1} sand (50–2000 μm particle size diameter), 711 ± 7 g kg^{-1} silt (2–50 μm diameter), and 230 ± 3 g kg^{-1} clay (<2 μm diameter). Selected soil properties were: pH (water) of 6.76 ± 0.02, 12.7 ± 0.4 g kg^{-1} total organic C, and 1.19 ± 0.01 g kg^{-1} total Kjeldahl N.

The soil was amended with ground (≤2-mm mesh) poultry litter (total organic C = 161 ± 28 g kg^{-1}; total N = 17.5 ± 0.1 g kg^{-1}) at 0 and 28.3 g kg^{-1} soil on a dry weight basis, which resulted in an addition of 0 and 496 mg total N kg^{-1} soil, respectively. The poultry litter was a mixture of turkey (*Meleagris gallopavo*) excrement plus pine shavings used as bedding material. The treated soil was moistened to 55% water-filled pore space (WFPS) by assuming a soil particle density of 2.65 Mg m^{-3}. The treated soil was uniaxially compacted into 76 mm by 76 mm diameter soil cores to four levels of dry bulk density (1.2, 1.4, 1.6 and 1.8 Mg m^{-3}) by using a compaction cylinder and hydraulic press. All treatments had three replicates. Each core was covered with a layer of gas-permeable parafilm (De Neve and Hofman, 2000) on one end, and placed in 2-l sealed polyvinyl jars containing 20 cm^3 of water to maintain humidity. Soil core samples were kept in a dark constant temperature room at 25 °C using the aerobic incubation method (Hart et al., 1994).

Soil CO_2 efflux was measured 1, 2, 3, 7, 14, 21, 28 and 42 days after the start of the incubation by first displacing the headspace of each jar with CO_2-free air and then sealing the jar with a screw-cap lid fitted with septa for gas sampling. After approximately 24 h, a 60-cm^3 syringe was used to uniformly mix the headspace of the jar and then a 3-cm^3 gas sample was taken from each jar. The concentration of CO_2 in the gas sample was measured using a gas chromatograph (GC). The GC used helium as a carrier gas at a flow rate of 20 cm^3 min^{-1}, a thermal conductivity detector set at 105 °C, and a 7.5-cm silica-gel column with the oven temperature adjusted to 50 °C. The CO_2 efflux was calculated based on the time CO_2 evolved, the weight of the soil in the core and the CO_2 concentration of the headspace and reported in μg CO_2–C g^{-1}soil day^{-1}.

Three replicates of treated soil cores were prepared for assessing soil physical properties using methods recommended by Klute (1986). Soil cores were slowly saturated from the bottom up with de-aired solution (6.06 g l^{-1} $CaCl_2$ and 1.78 g l^{-1} $MgCl_2$) at a rate of 3 mm h^{-1} (Palmer, 1979; Blanco-Canqui et al., 2004). The soil cores were subsequently measured for saturated hydraulic conductivity (K_{sat}) by the constant- or falling-head method (Klute and Dirksen, 1986). Pore size distribution was determined using water desorption from 0 to −40 kPa soil water pressure. Pore sizes were classified as macropores (>500 μm radius), coarse mesopores (25–500 μm radius), fine mesopores (5–25 μm radius) and micropores (<5 μm radius) (Anderson et al., 1990). After completing water retention measurements, about 20–30 g soil samples were removed from each core and oven-dried at 105 °C to determine gravimetric soil water content for calculating soil bulk density and total porosity.

2.2. Field study

This study was conducted during 2001 and 2002 at the Bradford Agronomy Center in the same field from which the bulk soil was collected for the laboratory incubation study. The study site is part of the central claypan region located in Missouri and Illinois (Soil Conservation Service, 1981). A previous study showed the depth to the claypan at this field site varied between 25 and 30 cm (Motavalli et al., 2003). Initial soil characteristics are given in Table 1. Daily and cumulative precipitation data were also obtained from the Bradford Agronomy Center (Fig. 1).

The experimental design used was a split block design arranged in randomized complete blocks with four replications. The experimental plots (3.0 by 6.1 m) were broadcast-applied with two levels of poultry litter (0 and 19.0 Mg litter ha^{-1} dry weight basis), containing an average of 316 ± 46 g kg^{-1} total organic C and 31 ± 3 g kg^{-1} total N. After incorporating litter into soil to a depth of approximately 15 cm with a disk, plots were surface-compacted 0 and 2 times with a tractor-pulled 1.9 m^3 water tank filled with water. The axle loads of the tractor and water tank were 2.5 and 2.9 Mg, respectively. The experiment contained both planted (i.e. to corn, *Zea mays* L.) and fallow (without plants) areas. Information presented in this paper was collected from the fallow area. Fallow plots were maintained free of weeds by periodic applications of glyphosate herbicide.

Table 1
Selected initial soil properties of unamended soil at the Bradford Agronomy Center in 2000

Depth (cm)	pH (water)	Total organic C (g kg^{-1})	Total N (g kg^{-1})	Soil inorganic N		Texture[b]		
				NH_4^+–N (mg kg^{-1})	NO_3^-–N (mg kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
0–10	6.04 ± 0.10[a]	15.7 ± 0.8	1.1 ± 0.1	3.23 ± 0.65	11.47 ± 1.60	57 ± 4	738 ± 15	206 ± 12
10–20	6.05 ± 0.16	14.7 ± 0.7	1.0 ± 0.1	2.99 ± 0.68	6.00 ± 1.89	50 ± 4	725 ± 19	225 ± 21
20–30	5.75 ± 0.33	13.5 ± 0.6	0.9 ± 0.1	3.09 ± 0.80	3.33 ± 1.78	36 ± 6	591 ± 83	373 ± 93

[a] Mean ± S.D.
[b] Effective particle size diameter of sand, silt and clay (50–2000, 2–50 and <2 μm, respectively).

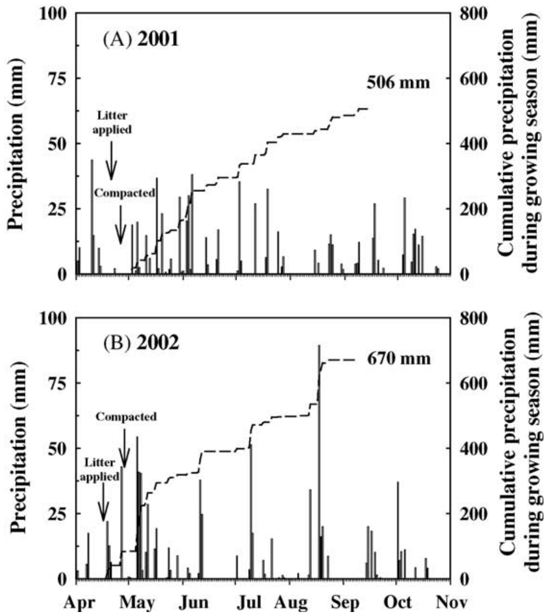

Fig. 1. Daily (bars) and cumulative precipitation (line) for the (A) 2001 and (B) 2002 growing seasons at the Bradford Agronomy Center, University of Missouri. Arrows indicate times of litter application and compaction events during the seasons.

Soil samples were collected using an Uhland probe in aluminum cores measuring 76 mm by 76 mm diameter at depths of 0–10, 10–20, and 20–30 cm. Soil cores were then used to determine soil bulk density (Blake and Hartge, 1986), K_{sat} (Klute and Dirksen, 1986), and total porosity and pore size distribution (Danielson and Sutherland, 1986).

Changes in soil CO_2 efflux were determined using a portable infrared CO_2 gas analyzer (LI-6200, LICOR Inc., Lincoln, NE, USA). Each plot had two 9.5 cm diameter PVC plastic soil collars pushed into the soil at a depth of approximately 2.5 cm. The distance between collars was approximately 1.5 m. Surface soil CO_2 efflux was determined by placing the LICOR CO_2-chamber onto the PVC collar and measuring changes in CO_2 concentration over time after the chamber CO_2 concentration had been lowered below ambient levels using a soda lime CO_2 trap. Surface soil temperature was determined using a soil temperature probe and gravimetric soil water content was measured by taking soil samples to a depth of 5 cm around each collar and oven-drying the soil at 105 °C. Soil CO_2 efflux was then calculated based on ambient CO_2 concentrations measured in the field and reported in μmol CO_2–C m^{-2} s^{-1} (Motavalli et al., 2000).

2.3. Statistical analysis

Analysis of variance (ANOVA) for evaluating the effects of compaction and poultry litter applications on soil CO_2 efflux and soil physical properties from both the laboratory incubation and the field experiment were determined by PROC GLM or PROC MIXED (SAS Institute, 2001). The statistical model used for the field experiment was a split plot in time. The multiple comparison test used was Fisher's (protected) LSD at $P \leq 0.05$. An exponential equation was fit to the data using non-linear regression to model the relationship between cumulative CO_2–C released in the laboratory incubation over time (Systat Software Inc., 2002). The first-order kinetic model was, $C_t = C_0(1 - e^{-kt})$, where C_0 and C_t are the cumulative CO_2–C in the soil at the initiation and at time (t) of incubation and k is the mineralization rate of C (day^{-1}). The relationship between soil physical properties and CO_2 efflux at day 28 of incubation was determined using Pearson linear correlation analysis (PROC CORR) and linear regression analysis (PROC REG) for soil bulk density.

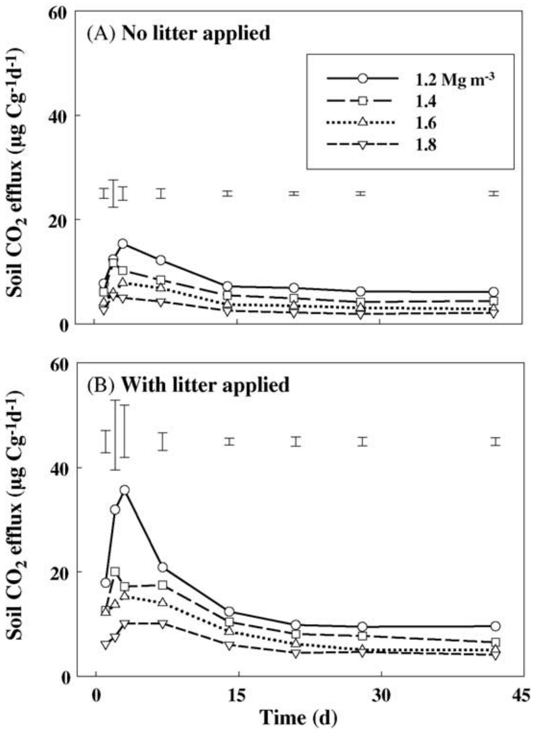

Fig. 2. Average soil CO_2 efflux with increasing soil bulk density and (A) no litter applied or (B) with litter applied for a 42-day incubation period. Vertical bars indicate $LSD_{(0.05)}$.

3. Results and discussion

3.1. C mineralization in the incubation study

Soil CO_2 efflux significantly decreased ($P < 0.05$) with increasing soil bulk density in both poultry-litter amended and unamended soils at all sampling times during the incubation (Fig. 2 A and B). With increasing soil bulk density, soil CO_2 efflux was lowered between 18–72 and 5–69% for litter amended and unamended soil, respectively, compared to the lowest bulk density (1.2 Mg m^{-3}). These results agree with findings of several other research studies with similar experimental designs. For example, Torbert and Wood (1992) found that soil CO_2 efflux was reduced 65% when soil bulk density increased from 1.4 to 1.8 Mg m^{-3} at 60% WFPS in loamy sand soils. De Neve and Hofman (2000) found that C mineralization of a loamy sand soil amended with plant residues was significantly depressed in compacted treatments, especially with a soil bulk density of 1.6 Mg m^{-3}.

As expected, increasing soil bulk density significantly ($P < 0.05$) reduced K_{sat}, total porosity, and shifted the proportion of larger pores (especially macropores) to smaller pores (micropores) (Table 2). However, the mixing of poultry litter did not result in consistent increases in porosity and changes in pore size distribution (Table 2), probably because soil bulk density levels were established in this study after the litter was added to the soil. Compaction, which results in increased soil bulk density, can limit fluid and gas transport, reduce water availability and limit soil aeration that may reduce soil microbial activity.

During the incubation, soil CO_2 efflux of all treatments ranged from 2 to 36 μg CO_2–C g^{-1} day^{-1} and was highest in the first 14 days and subsequently decreased and stabilized (Fig. 2A and B). This pattern suggests high initial soil microbial activity and a possible rapid growth rate of soil microorganisms in the beginning of the incubation, due to the presence of readily available substrates (Liebig et al., 1995) that are likely the results of soil handling (drying, sieving and re-wetting) and the addition of more easily decomposable compounds from the poultry litter. The phase of stable soil CO_2 efflux was possibly the activity of slow-growing soil microorganisms. Liebig et al. (1995) also found that soil CO_2 efflux ranged from 1.1 to 36.0 μg CO_2–C g^{-1} day^{-1} (recalculated figures) in silty clay loams at 47, 61 and 73% WFPS. The average soil CO_2 efflux of this study over the incubation period was 2.51–7.42 μg CO_2–C g^{-1} day^{-1} in unamended soils and 5.42–12.50 μg CO_2–C g^{-1} day^{-1} in litter-amended soils. Jensen et al. (1996a) found average soil CO_2 efflux in silty clay loam soils was 15 and 21 μg CO_2–C g^{-1} day^{-1} for soils from a 28-year cropped site and from a 10-year continuously maize-cropped site, respectively. The difference in average CO_2 efflux observed in this study compared to other studies can possibly be attributed to the longer incubation time of this study (42 days) compared to the Jensen et al. (1996a) study (28 days) and differences in analytical methods used (GC and NaOH-trapping methods) for measuring CO_2 efflux.

As expected, soil CO_2 efflux was significantly greater in poultry-litter amended soils than unamended soils ($P < 0.05$). This indicates applied litter had a positive effect on soil CO_2 efflux, potentially because of more readily available C forms and greater amounts of nutrients added in the litter relative to native soil

Table 2
Effects of surface compaction and poultry litter application on selected soil physical properties in the incubation study

Bulk density ($Mg\ m^{-3}$)	K_{sat}[a]			Total porosity			Pore size distribution											
							Macropores[b]			Coarse mesopores			Fine mesopores			Micropores		
	Check (log (cm h^{-1}))	Litter (log (cm h^{-1}))	LSD[c] (log (cm h^{-1}))	Check ($m^3\ m^{-3}$)	Litter ($m^3\ m^{-3}$)	LSD ($m^3\ m^{-3}$)	Check (%$m^3\ m^{-3}$)	Litter (%$m^3\ m^{-3}$)	LSD (%$m^3\ m^{-3}$)	Check (%$m^3\ m^{-3}$)	Litter (%$m^3\ m^{-3}$)	LSD (%$m^3\ m^{-3}$)	Check (%$m^3\ m^{-3}$)	Litter (%$m^3\ m^{-3}$)	LSD (%$m^3\ m^{-3}$)	Check (%$m^3\ m^{-3}$)	Litter (%$m^3\ m^{-3}$)	LSD (%$m^3\ m^{-3}$)
1.2	2.200	1.827	0.345	0.546	0.547	NS	4.01	5.03	NS	23.10	21.84	NS	8.96	9.76	NS	63.93	63.37	NS
1.4	−0.417	−0.737	0.063	0.473	0.475	NS	2.52	4.50	1.92	3.68	4.89	NS	19.38	15.64	1.57	74.43	74.98	0.38
1.6	−1.617	−1.727	NS	0.434	0.444	0.004	2.30	0.66	NS	1.09	3.45	0.93	10.49	9.79	NS	86.12	86.09	NS
1.8	−2.043	−1.997	NS	0.406	0.414	NS	0.45	0.53	NS	2.13	1.46	NS	5.90	6.05	NS	91.52	91.96	NS
LSD	0.232	0.236		0.007	0.008		1.44	1.83		1.99	1.91		0.70	1.35		1.39	2.02	

[a] K_{sat} (saturated hydraulic conductivity).
[b] Macropores (>500 μm radius), coarse mesopores (25–500 μm radius), fine mesopores (5–25 μm radius) and micropores (<5 μm radius).
[c] LSD is least significant difference at $P < 0.05$; NS = not significant.

organic matter. This finding is in agreement with results found by De Neve and Hofman (2000) using crop residues as an organic amendment and Chantigny et al. (2001) who observed increased specific respiration activity (i.e. the ratio of CO_2–C fluxes to microbial biomass C) in slurry manure-amended soil.

As was found with CO_2 efflux, cumulative CO_2–C released was significantly reduced with increasing soil bulk density for both litter-amended and unamended soil (Fig. 3). First-order kinetic models for the relationship between cumulative CO_2–C released and time at different bulk densities had high coefficients of determination ($r^2 = 0.86$–0.99; $P < 0.001$) (Fig. 3). According to the kinetic models, potentially mineralizable C (C_0) and mineralization rate (k) were predicted. Predicted C_0 tended to be lower with

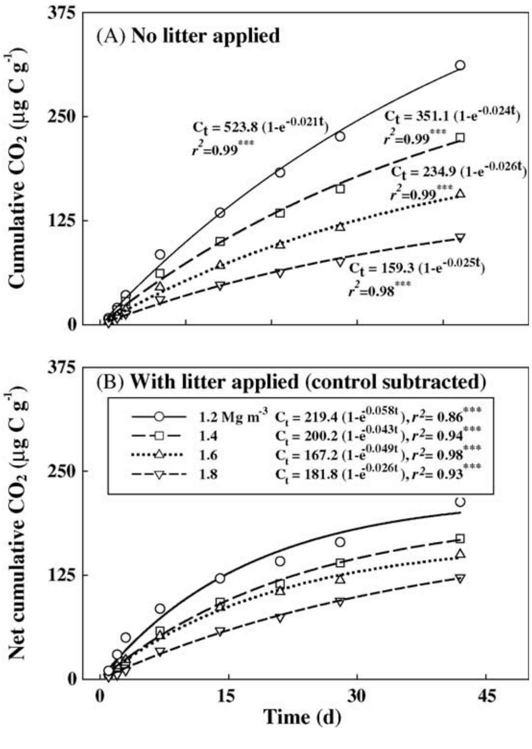

Fig. 3. Cumulative or net cumulative CO_2 with increasing soil bulk density and (A) no litter applied or (B) with litter applied (control subtracted) for 42-day incubation period. Lines are predicted non-linear regression models using first-order kinetics [$C_t = C_0 (1 - e^{-kt})$, where C_0 and C_t are the cumulative CO_2 (μg C g^{-1} soil) in the soil at the initial and time (t) of incubation and k is the mineralization rate of C (day^{-1})]. (***) Represents significance at $P < 0.001$.

Table 3
Correlation coefficients (r) between soil CO_2 efflux at day 28 of incubation and soil physical properties

Soil physical property	CO_2 efflux	
	r	$P > F$
Bulk density	−0.79	0.020
Log K_{sat}[a]	0.70	0.052
Total porosity	0.78	0.014
Macropores[b]	0.81	0.015
Coarse mesopores	0.69	0.058
Fine mesopores	0.21	NS[c]
Micropores	−0.77	0.027

[a] K_{sat} (saturated hydraulic conductivitiy).
[b] Macropores (>500 μm radius), coarse mesopores (25–500 μm radius), fine mesopores (5–25 μm radius), and micropores (<5 μm radius).
[c] NS (not significant at 0.10 level).

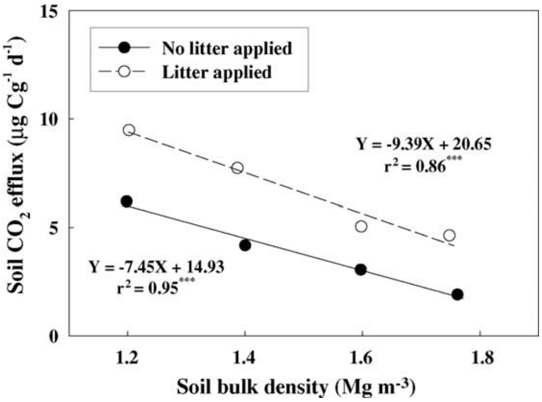

Fig. 4. The relationship between soil bulk density and soil CO_2 efflux at day 28 of incubation. (***) Indicates $P < 0.001$. Lines are predicted values based on linear regression models.

increasing soil bulk density, especially for unamended soil. Compaction had a greater tendency to reduce the mineralization rate of the amended soil, and had less effect on unamended soil. This result suggests that soil compaction limited the accessibility of C substrates from soil micro-organisms, possibly due to physical protection. In general, k was higher in amended soil compared to unamended soil, possibly because of more readily available C substrates from the added litter.

3.2. Relationship between soil CO_2 efflux and soil physical properties

Correlation coefficients between soil CO_2 efflux and soil physical properties were determined with soil CO_2 efflux values after 28 days of incubation when CO_2 efflux became stable (Table 3). Soil CO_2 efflux was positively related ($P < 0.05$) with total porosity and the proportion of macropores in the soil. These soil physical properties affect soil hydraulic properties, which support soil aeration, water and gas transport, and, consequently, produce favorable aerobic conditions for soil microorganisms. In contrast, soil CO_2 efflux had significant negative relationships with soil bulk density and the proportion of micropores ($P < 0.05$) in the soil. Dense soils with high soil bulk density and micro-porosity limit the capacity of soil fluid and gas transport, which in turn reduces the accessibility of soil microorganisms to soil air and water, creating a less favorable environment for soil microorganisms. Under conditions of higher soil bulk density, soil CO_2 efflux was restricted. A similar observation was also reported by Liebig et al. (1995), who found a significant negative correlation of soil bulk density with soil CO_2 efflux but also a significant positive correlation with K_{sat} under several soil water contents in a silty clay loam soil. Li et al. (2002) observed that the numbers of soil bacteria, fungi and actinomycetes were decreased 26–39% with increased soil bulk density.

Soil CO_2 efflux at 28 days of incubation and bulk density had a significant linear relationship for both litter amended ($r^2 = 0.86$, $P < 0.001$) and unamended ($r^2 = 0.95$, $P < 0.001$) soils (Fig. 4). These results suggest that stabilized soil CO_2 efflux may potentially be predicted based on soil bulk density under conditions of optimum water-filled pore space. The slope of the regression equation for CO_2 efflux rate was slightly higher in the litter amended soil ($a = -9.39$) than in the control ($a = -7.45$) (Fig. 4). Therefore, C mineralization in the litter amended soil was more depressed with higher soil bulk density compared to the unamended soil. De Neve and Hofman (2000) also found a similar result in a loamy sand.

3.3. Surface soil CO_2 efflux in the field study

The surface compaction treatment imposed in the field study significantly affected soil physical properties in the 0–20 cm depth for 2001 and in the 0–10 cm depth for 2002 field seasons (Table 4). Compaction significantly increased soil bulk density and decreased

Table 4
Effect of compaction on selected soil physical properties in the field study in 2001–2002

Soil properties	Soil depth (cm)								
	0–10			10–20			20–30		
	Non-compacted	Compacted	$P > F$	Non-compacted	Compacted	$P > F$	Non-compacted	Compacted	$P > F$
Year 2001									
Bulk density ($Mg\ m^{-3}$)	1.24	1.39	0.071	1.38	1.46	0.052	1.36	1.41	NS[a]
K_{sat} ($cm\ h^{-1}$)	207.07	44.48	0.057	56.47	143.04	NS	17.02	26.86	NS
Total porosity ($m^3\ m^{-3}$)	0.531	0.473	0.068	0.479	0.448	0.086	0.485	0.469	NS
Macropores[b] (%)	6.33	4.08	0.061	3.79	3.70	NS	3.82	2.41	NS
Coarse mesopores (%)	15.31	10.29	0.077	10.80	9.96	NS	11.35	9.14	NS
Fine mesopores (%)	7.72	7.35	NS	6.71	5.30	NS	7.26	6.64	NS
Micropores (%)	70.64	78.29	0.078	79.55	80.20	NS	77.57	81.80	NS
Year 2002									
Bulk density ($Mg\ m^{-3}$)	1.27	1.40	0.024	1.42	1.49	NS	1.34	1.34	NS
K_{sat} ($cm\ h^{-1}$)	127.97	33.31	0.063	10.23	4.65	NS	3.05	5.86	NS
Total porosity ($m^3\ m^{-3}$)	0.521	0.470	0.026	0.462	0.436	NS	0.494	0.492	NS
Macropores (%)	4.83	2.22	0.021	2.52	1.47	NS	1.80	1.16	NS
Coarse mesopores (%)	14.37	8.81	0.087	6.38	5.45	NS	5.52	7.02	NS
Fine mesopores (%)	9.67	8.15	NS	6.74	5.53	NS	7.22	5.58	NS
Micropores (%)	71.12	80.76	0.012	84.36	87.55	NS	85.46	86.25	NS

[a] NS (not significant at $P > 0.10$).
[b] Macropores (>500 μm radius), coarse mesopores (25–500 μm radius), fine mesopores (5–25 μm radius) and micropores (<5 μm radius).

K_{sat} and total porosity. Pore size distribution was also shifted from larger pores to smaller pores so that the proportions of macropores and coarse mesopores were reduced while the proportion of micropores was increased in the compacted soil. These effects of soil compaction were observed despite the relatively moderate axle load of 2.5–2.9 Mg applied to the soil surface in this study (Motavalli et al., 2003).

Both soil compaction and applied poultry litter had significant effects on soil CO_2 efflux, but were not consistent between the 2 years of the study (Table 5).

Table 5
Analysis of variance (ANOVA) of field soil CO_2 efflux for main and interactive effects of soil compaction, poultry litter treatment (TRT) and time (measuring dates)

Source of variation	$P < F$	
	2001	2002
Replication (R)	0.387	<0.001
Soil compaction (C)	0.108	0.025
Treatments (TRT)	<0.001	<0.001
C × TRT	0.041	0.306
Time	<0.001	<0.001
C × time	0.007	<0.001
TRT × time	<0.001	<0.001
C × TRT × time	0.168	0.606

During 2001, only the litter treatments and sampling date had significant effects on measured soil CO_2 efflux. Significant interactions between compaction and litter treatment, compaction and sampling date and litter treatment and sampling date were also observed (Table 5). During the 2002 season, all main factors and two-way interactions were significant, except the interaction between compaction and litter treatment. Differences between the 2 years in effects of compaction may have occurred because of the relatively lower amount of precipitation during the 2001 growing season (506 mm) compared to precipitation during the 2002 season (670 mm). Variation in the effects of soil compaction on microbial activity may be caused by soil aeration (Whalley et al., 1995). In dry years, compacted soil may retain soil water longer for soil microorganisms, which results in the promotion of soil microbial activity, detected as soil CO_2 production, relative to non-compacted soil. In wet years, compaction may lead to wet or saturated soil due to poor water infiltration causing denitrification and potentially limiting aerobic microbial activity.

In general, surface soil CO_2 efflux during the two years was higher at the beginning of the cropping season after litter had been applied (May to June) and

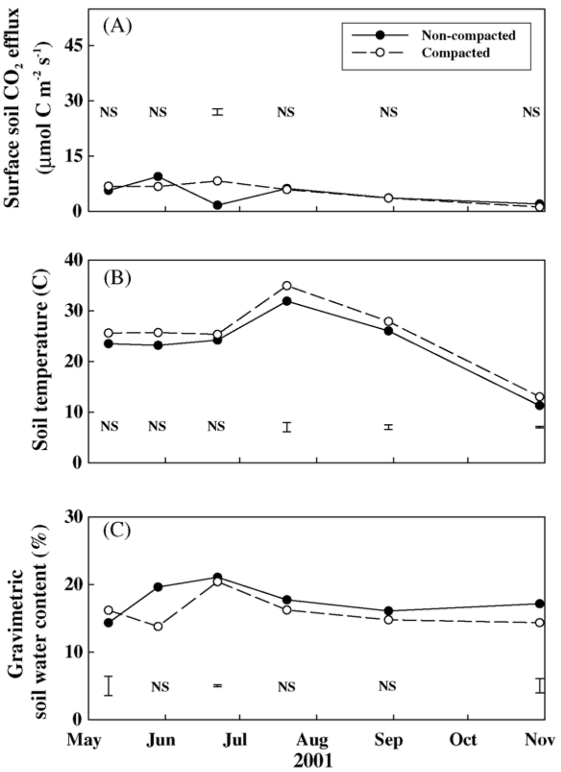

Fig. 5. The effects of soil compaction on (A) surface soil CO_2 efflux, (B) soil temperature and (C) gravimetric soil water content during the cropping season in 2001. Vertical bars indicate Duncan's critical range at $\alpha = 0.05$ and NS is not significant.

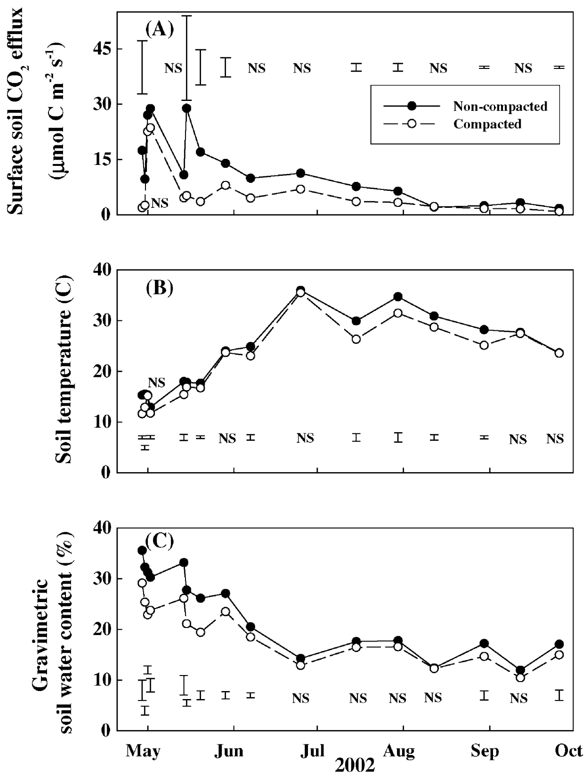

Fig. 6. The effects of soil compaction on (A) surface soil CO_2 efflux, (B) soil temperature and (C) gravimetric soil water content during the cropping season in 2002. Vertical bars indicate Duncan's critical range at $\alpha = 0.05$ and NS is not significant.

decreased with time (Figs. 5–8). This pattern was similar to that observed in the incubation study (Fig. 2). As gravimetric soil water content (SWC) decreased to approximately 15–20% and soil temperatures reached 25–30 °C later in the cropping season (around August and September), soil CO_2 efflux gradually decreased and became stable. The pattern of soil CO_2 efflux was positively correlated with soil water content ($r = 0.44$; $P < 0.001$), and negatively related with soil temperature ($r = -0.26$; $P < 0.001$). Therefore for this site, soil CO_2 efflux was more dependent on changes in soil water content than soil temperature.

Since surface soil compaction did not significantly affect soil CO_2 efflux in 2001, these data are not discussed (Fig. 5). However, the compaction treatment significantly depressed soil CO_2 efflux throughout 2002 ($P < 0.05$; Fig. 6). During the 2002 cropping season, the average soil CO_2 efflux of compacted soils (6.12 μmol CO_2–C m^{-2} s^{-1}) was reduced 46% relative to that of the non-compacted soil (11.47 μmol CO_2–C m^{-2} s^{-1}). In the field, compaction affected soil CO_2 efflux in a similar trend observed in the lower range of soil bulk density in the incubation study because of the relatively moderate increase in soil bulk density achieved in the field study (1.27 Mg m^{-3} of non-compacted soil and 1.40 Mg m^{-3} of compacted soil at 0–10 cm depth). The rate of CO_2 efflux observed in the field study was lower than that observed by Jensen et al. (1996b), who reported between 57 and 69% reduction in CO_2 efflux due to compaction. Possible reasons for differences in the effects of compaction between the two studies are because of the lower organic C content (1.27% C) of the soil used in this study compared to the soil used in the study of Jensen et al. (1996b); 2.1% C and the different methods used for determining soil CO_2 efflux (i.e. portable infrared CO_2 gas analyzer and NaOH-trapping methods).

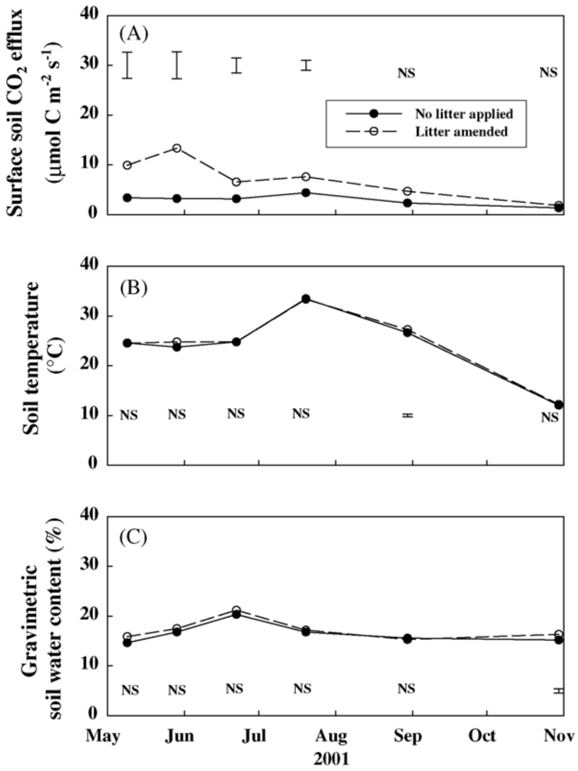

Fig. 7. The effects of applied poultry litter on (A) surface soil CO_2 efflux, (B) soil temperature and (C) gravimetric soil water content during the cropping season in 2001. Vertical bars indicate Duncan's critical range at $\alpha = 0.05$ and NS is not significant.

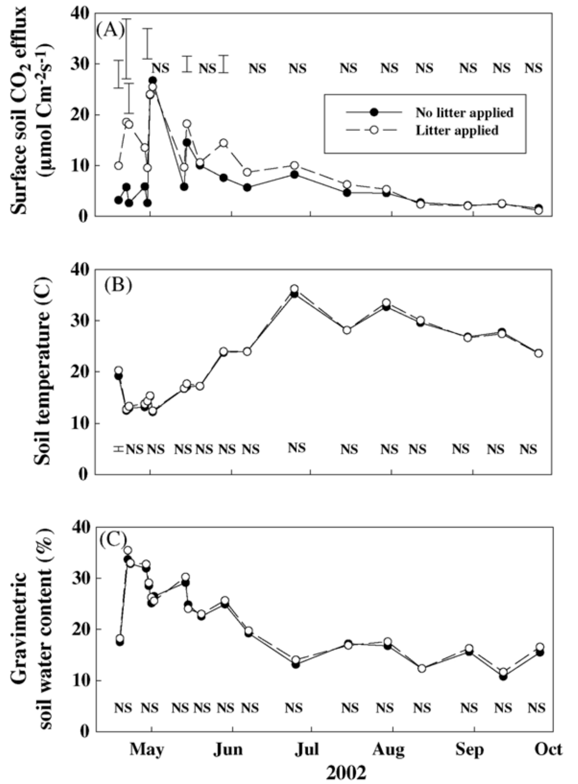

Fig. 8. The effects of applied poultry litter on (A) surface soil CO_2 efflux, (B) soil temperature and (C) gravimetric soil water content during the cropping season in 2002. Vertical bars indicate Duncan's critical range at $\alpha = 0.05$ and NS is not significant.

Soil water content and temperature were also affected by compaction. Generally, compacted soil had lower soil water content than non-compacted soil (Figs. 5C and 6C). After compaction, the soil had a higher soil bulk density with a lower capacity for water infiltration, especially in short-term drought periods, resulting in less available water for soil microorganisms and limiting microbial activity. Soil temperature was generally higher in compacted soil compared to non-compacted soil in 2001 (Fig. 5B). In contrast, non-compacted soil had higher soil temperature relative to compacted soil in 2002 (Fig. 6B). The differences observed between the two years are possibly because the soil CO_2 measurements taken in 2002 were affected by diurnal variation in soil temperature since the measurement began with the compacted plots and was followed by the non-compacted area from about 8 a.m. to 2 p.m. However, soil CO_2 measurements during 2001 were conducted over a complete replication, which possibly minimized diurnal variations in soil temperature. These observations indicate that compacting the soil negatively influences water infiltration rates and storage capacity and requires less energy to warm up compared to non-compacted soil.

Effects of added poultry litter on soil CO_2 efflux were significant in both years ($P < 0.001$; Table 5), especially in the early part of the season (Figs. 7A and 8A). Litter-amended soils had higher soil CO_2 efflux compared to unamended soil by an average of 2.4 times in 2001 and 1.4 times in 2002. Soil CO_2 efflux in 2001 was relatively lower than in 2002, particularly in the beginning of cropping season, possibly due to lower precipitation during 2001 (Fig. 1). Generally, soil temperature and soil water content were higher, but inconsistently significant, in litter-amended soils compared to unamended soils (Figs. 7 and 8). Other researchers have also observed higher soil water-holding capacity in manure-amended soils (Khaleel et al., 1981). However, higher soil temperature observed in this study in litter-amended soil has not been commonly observed and may be caused by several possible factors, including a lower albedo with added organic material (Kongoli and Bland, 2002) and higher soil biological activity (Rochette et al., 2000). Rochette et al. (2000) observed that plots receiving annual applications of pig slurry for 19 years had an inconsistently higher soil temperature relative to an unamended plot.

4. Conclusions

Surface soil compaction in claypan soils has an effect on several soil physical properties, which cause reductions in soil C mineralization. Our results suggest that changes in soil water content and soil aeration caused by surface compaction may have the largest influence on variations in soil CO_2 efflux in these soils. These effects are also modified by climate so that in a relatively wet year, we observed significant reductions in soil CO_2 efflux but under drier conditions, soil CO_2 efflux was not affected by surface compaction. Observed changes in soil physical properties due to compaction that affect soil CO_2 efflux included changes in K_{sat}, total porosity, pore size distribution and soil bulk density. Under controlled soil moisture conditions, we observed that soil bulk density may be a significant predictor of soil CO_2 efflux. Applying poultry litter increased soil CO_2 efflux in both compacted and non-compacted soils at several levels of soil bulk density. Incorporation of litter provided more favorable conditions for soil microbial activity, including higher soil water content and temperature, and possibly more organic C to the soil. As a result, the application of litter can potentially modify the effects of soil compaction on both soil physical and biological properties that may affect crop production and environmental contamination.

Acknowledgements

We wish to acknowledge the generous funding by the System Research Board of the University of Missouri for supporting this research. We are also very thankful for the technical assistance provided by Tim Reinbott, Jenan Nichols, Dennis Wambuguh, John Dodds, and Josh Intveld to this research. Additional assistance was also provided by Nancy Mungai and Neal Bailey.

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