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Authors: Miller, J.J., Owen, M.L., Drury, C.F., and Chanasyk, D.S.

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ARTICLE

Short-term legacy effects of feedlot manure amendments on surface soil CO_2 efflux under irrigated silage barley in Southern Alberta

J.J. Miller, M.L. Owen, C.F. Drury, and D.S. Chanasyk

Abstract: The short-term legacy effects following long-term (17 yr) feedlot manure application on CO_2 efflux for a surface soil (clay loam) were studied over 2 yr (2016–2017) on a Dark Brown Chernozem in southern Alberta. The five treatments were stockpiled (SM) or composted (CM) manure with either straw (ST) or wood-chips (WD) bedding applied at 77 $Mg \cdot ha^{-1}$ (dry wt.) and an unamended control (CON). Surface soil efflux was measured during the growing season of the 2 yr using the dynamic, closed-chamber method. Ancillary measurements (soil water and temperature, total carbon, bulk density) were also obtained. Soil CO_2 efflux was similar ($P > 0.05$) among the four amended treatments in the first (0.63–0.86 $g \cdot m^{-2} \cdot h^{-1}$) and second (0.40–0.46 $g \cdot m^{-2} \cdot h^{-1}$) years. However, soil CO_2 efflux was significantly greater for amended than unamended treatments by 54–110% in the first year (CON = 0.41 $g \cdot m^{-2} \cdot h^{-1}$) and by 33–53% in the second year (CON = 0.30 $g \cdot m^{-2} \cdot h^{-1}$). Soil CO_2 efflux was similar for SM and CM in both years and was significantly greater for WD than ST bedding in the first but not second year. Weak positive correlations ($r \le 0.39$) occurred between soil CO_2 efflux and total soil C, water-filled pore space (WFPS), and soil temperature. Overall, our findings suggested that legacy effects of manure may persist for 1–2 yr following discontinued applications, but are mostly restricted to greater soil CO_2 efflux for amended than unamended soils.

Key words: legacy effects, feedlot manure, soil CO_2 efflux, manure type, bedding material.

Résumé : Pendant deux ans (2016 et 2017), les auteurs ont étudié les effets résiduels à court terme de dix-sept années d'application de fumier de bovins sur le volume de CO_2 libéré par un loam argileux recouvrant en surface un tchernoziom brun foncé, dans le sud de l'Alberta. Les quatre traitements étaient les suivants : application de 77 Mg (poids sec) de fumier de copeaux de bois (CB) ou de paille, empilé (FE) ou composté (FC), par hectare. S'y ajoutait un témoin. Les dégagements ont été mesurés chaque année pendant la période végétative par la méthode de la chambre close dynamique. Les auteurs ont également pris d'autres mesures (teneur en eau et température du sol, concentration totale de carbone, masse volumique apparente). Les émissions de CO_2 du sol étaient similaires ($P > 0,05$) pour les quatre traitements la première (0,63–0,86 $g \cdot m^{-2} \cdot h^{-1}$) et la deuxième (0,40–0,46 $g \cdot m^{-2} \cdot h^{-1}$) année. Cependant, elles étaient nettement plus importantes pour le sol amendé que pour celui qui ne l'avait pas été, soit de 54 à 110 % la première année (témoin = 0,41 $g \cdot m^{-2} \cdot h^{-1}$) et de 33 à 53 % la deuxième (témoin = 0,30 $g \cdot m^{-2} \cdot h^{-1}$). Les dégagements de CO_2 des sols FE et FC étaient semblables les deux années, mais ceux de la litière CB ont nettement dépassé les émissions de la litière de paille la première des deux années. Il existe une faible corrélation positive ($r \le 0,39$) entre les dégagements de CO_2 du sol et la concentration totale de C, l'espace interstitiel empli d'eau et la température du sol. Dans l'ensemble, ces constatations laissent croire que les effets résiduels du fumier peuvent persister un an ou deux après interruption de l'épandage, mais se résument en grande partie à des dégagements de CO_2 plus importants pour les sols amendés que pour ceux qui ne le sont pas. [Traduit par la Rédaction]

Mots-clés : effets résiduels, fumier de bovins, émissions de CO_2 du sol, type de fumier, litière.

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J.J. Miller and M.L. Owen. Agriculture and Agri-Food Canada, 5403-1st Ave. South, Lethbridge, AB T1J 4B1, Canada.

C.F. Drury. Agriculture and Agri-Food Canada, 2585 County Road 20, Harrow, ON N0R 1G0, Canada.

D.S. Chanasyk. Department of Renewable Resources, University of Alberta, Room 751, General Services Bldg., Edmonton, AB T6G 2H1, Canada.

Corresponding author: J.J. Miller (email: millerjim335@gmail.com).

Introduction

The termination of long-term application of feedlot manure to irrigated barley grown for silage may result in legacy (residual) treatment effects on soil carbon dioxide (CO_2) efflux. Carbon dioxide release from the soil surface is termed soil respiration, soil CO_2 evolution, or CO_2 efflux (Raich and Schlesinger 1992). Total global emissions of CO_2 from soils are recognized as one of the largest fluxes in the global carbon cycle, and small changes in the magnitude of soil respiration could have a large effect on the concentration of CO_2 in the atmosphere (Schlesinger and Andrews 2000).

Critical factors influencing soil CO_2 efflux include temperature, soil moisture or water-filled pore space, aeration and gas diffusivity, quantity and quality of available carbon (C) and nitrogen (N), C/N ratio, pH, available nutrients, osmotic potential or salinity, vegetation quality, net ecosystem productivity, relative allocation of net primary productivity to above- and below-ground, population and community dynamics of the above-ground vegetation and below ground flora and fauna, land use, and other factors (Rochette et al. 1991; Gregorich et al. 1998; Rustad et al. 2000; Ginting et al. 2003; Ryan and Law 2005; Ding et al. 2007; Heller et al. 2010). Under dryland and semi-arid conditions of southern Alberta, soil moisture was identified as the main parameter controlling soil respiration during the growing season (Akinremi et al. 1999). The legacy effect of organic amendments on soil microorganisms has been attributed to the decomposition of organic matter, plant growth, and changing edaphic factors (Zhang et al. 2018). When organic carbon is added to the soil such as by manure application and substrate availability increases, soil respiration is generally enhanced by greater microbial activity (Schlesinger and Andrews 2000).

Previous research has found that one-time or annual applications of various raw and composted organic amendments (animal manure, municipal wastes, crop residues) typically enhances soil CO_2 emissions compared with inorganic fertilizers or unamended treatments (Hadas et al. 2004; Jones et al. 2005; Ding et al. 2007; Johnson et al. 2007; Ellert and Janzen 2008; Heller et al. 2010; Miller et al. 2014). However, little research has been conducted on the legacy effects of discontinued feedlot manure application to cropland on soil CO_2 efflux (Ginting et al. 2003). The latter authors applied annual and biennial fresh and composted feedlot (beef) manure to a silty clay loam soil cropped to corn for 4 yr and then measured soil CO_2 efflux 4 yr after applications were stopped. They found no significant difference in CO_2 efflux between amended and unamended control or inorganic fertilized treatments.

Manure types such as stockpiled (SM) or composted (CM) with either straw (ST) or wood-chip (WD) bedding may also influence soil CO_2 emissions, but little research has compared these treatments during the legacy period following termination of long-term manure applications. Miller et al. (2014) generally found similar instantaneous soil CO_2 fluxes under wood-chip and straw treatments with stockpiled manure after 13–14 yr of continual annual applications. The total C content of the four manure amendment types and bedding treatments followed the order SM-WD > CM-WD > SM-ST > CM-ST (Miller et al. 2009). Mean total C for the amendments was also greater for SM than CM manure type and greater for WD than ST bedding. Therefore, we hypothesized that soil CO_2 effluxes might follow the same trend as for total C of the amendments.

The objective of our study was to determine if short-term legacy effects of long-term feedlot manure application occurred on soil CO_2 efflux. The five treatments compared were stockpiled (SM) or composted (CM) feedlot manure with either straw (ST) or wood-chip (WD) bedding at 77 $Mg{\cdot}ha^{-1}$ (dry wt.) and an unamended control (CON). We hypothesized that legacy soil CO_2 efflux would (*i*) be significantly different among the four amended treatments, (*ii*) be greater for amended than unamended control treatments, and (*iii*) be greater for SM than CM manure types and for WD than ST bedding material.

Materials and Methods

The long-term field experiment is located at Lethbridge in southern Alberta, Canada. The area is semi-arid with long-term annual precipitation of 406 mm and total evaporation of 1299 mm. The clay loam soil is classified as a Dark Brown Chernozem. The details of the field experiment have been previously reported (Miller et al. 2009, 2014). We utilized 20 of the 56 treatment plots for this study. The treatments (four replications) utilized were stockpiled (SM) or composted (CM) feedlot manure with straw (ST) or wood-chip (WD) bedding applied at 77 $Mg{\cdot}ha^{-1}$ (dry wt.), with an unamended control (CON) treatment.

The SM was stored outside in a pile for up to 2 mo prior to land application and has been referred to as fresh manure in some previous studies at this site. The CM was composted by the windrow method (Larney et al. 2003) and turned approximately seven times over a 90 d period (active phase), followed by a curing phase (no turning) for another 90–120 d. The ST bedding was uncut barley straw sourced from local producers. The WD bedding was a mixture of 50% fine sawdust and 50% wood chips, bark, and post peelings, obtained from Sundre Forest Products (West Fraser Mills Ltd.) in Sundre, AB. The trees were a 4:1 mixture of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and white spruce (*Picea glauca* (Moench) Voss).

Selected chemical and physical properties of the four manure treatments have been previously reported (Miller et al. 2009). The percentage of fine (<7.1 mm) particles in the four amendments followed the order

CM-WD > SM-WD > CM-ST > SM-ST and was the reverse order for coarse (>7.1 mm) sizes. Visual observations in the field indicated that ST particles in the soil were rapidly decomposed, whereas larger chunks of WD bark persisted for much longer. The WD bedding has a greater C/N ratio, lower pH, and higher lignin content than ST bedding (Miller et al. 2003).

The feedlot amendments were applied for 17 consecutive years (1998–2014) and then discontinued thereafter (2015–2017). Therefore, soil sampling and measurements in 2016 and 2017 were 1 and 2 yr (legacy phase) after manure applications were terminated in 2015. No inorganic fertilizer was applied with the organic amendments. The amendments were applied in late fall after harvest and incorporated to a depth of about 20 cm using an offset-disc cultivator. The crop was irrigated (wheel-move) barley (*Hordeum jubatum*) grown for silage. The crop was typically seeded in May and harvested in August at the soft dough stage.

Irrigation (38.1 mm for each event) was applied three times in June (June 14, 20, 29) and one time in July (July 6) of 2016, for a total amount of 152.4 mm. In 2017, 25.4 mm of irrigation was applied on June 12, 38.1 mm was applied for each irrigation five times in June (June 21, 28) and July (4, 10, 19), and 50.8 mm was applied for each irrigation five times in August (August 18, 22, 24, 28, 30), for a total of 469.9 mm. Three times more irrigation was applied in 2017 than 2016 because of another simultaneous study that required irrigation for each replicate to facilitate earthworm sampling in 2017 (Miller et al. 2019a). Total precipitation at Lethbridge from April 1 to August 31 was greater in 2016 (208.8) than 2017 (174.6 mm), which was below the long-term normal precipitation of 221.1 mm. Total irrigation and precipitation (April 1–August 31) were 1.8 times greater in 2017 (644.5 mm) than 2016 (361.2 mm).

Soil surface CO_2 efflux or respiration rates (instantaneous point measurements) were measured using a portable infrared gas analyzer (IRGA) system consisting of an EGM-4 Environmental Gas Monitor attached to an SRC-1 Soil Respiration (15 cm height × 10 cm diameter) closed-dynamic-chamber (PP Systems, Hertfordshire, UK). The EGM-4 monitor is accurate to within 1% of the calibrated range (0–2000 ppm CO_2), and the SRC-1 accurate to within 1% of the calibrated range (0–9.99 g $CO_2 \cdot m^{-2} \cdot h^{-1}$). Instantaneous soil CO_2 efflux was measured according to the manufacturer's recommendation and as reported by Pacific et al. (2008). Before each measurement, the chamber was flushed with ambient air for 15 s and then inserted into the soil to ensure a good seal between the chamber and the ground surface. The sampling period lasted for 120 s or until the CO_2 concentration inside the chamber increased by 60 ppm. To determine the CO_2 efflux during the measurement, a quadratic equation was fitted to the relationship between the increasing CO_2 concentration and elapsed time.

Soil efflux measurements (once in May, twice between June and August) were generally taken in the morning six times (May 5, June 1, June 20, July 21, August 5, August 26) during the growing season in 2016 and seven times (May 23, June 8, June 21, July 7, July 21, August 1, August 16) during the growing season in 2017. If irrigation was applied on these CO_2 measurement dates, the efflux measurements were always taken prior to irrigation. Volumetric water content and temperature of the soil surface were measured at the same time and adjacent to the soil efflux chamber using a Procheck PC-1 meter and GS3 probe (Decagon Devices, Pullman, WA). The GS3 probe has a length of 5.5 cm and measures a 160 cm^3 sample volume of soil. The water-filled pore space (WFPS) was calculated as the quotient of volumetric water content divided by soil porosity, which was calculated from soil bulk density (Liu et al. 2007). Total C of the surface (0–5 cm) soil in 2016 and 2017 was measured on unacidified soil samples following the Dumas automated combustion technique (McGill and Figueiredo 1993) with a C-N-sulfur (CNS) analyzer (CE Instruments, Milan, Italy). Organic C comprises 91% of the total C in the unamended soil and 98–100% of total C in amended soils (J.J. Miller, unpublished).

Statistical analysis

Statistical analysis was conducted using a mixed model analysis with SAS software (SAS Institute Inc. 2012). If required, data were log-transformed to obtain a normal distribution and homogeneous variances. Two mixed model analyses were conducted using amendment treatment as fixed effect and replicate as random effect. The first analysis analyzed the effect of all five treatments (SM-ST, SM-WD, CM ST, CM-WD, CON) on soil CO_2 efflux and also used pairwise comparisons (estimate statements in SAS) to compare amended versus unamended CON treatments. The second analysis examined the effect of the treatment factors manure type (SM vs. CM) and bedding material (ST vs. WD) on soil CO_2 efflux. The unamended CON treatment was omitted for this latter analysis because there was only one level of this factor. Pearson correlation analysis ($P \leq 0.05$) was conducted to determine possible relationships between soil CO_2 efflux and soil total C, WFPS, and soil temperature.

Results

Ancillary measurements

Mean total C concentration for the four amended treatments (78.8–122 $g \cdot kg^{-1}$ over the 2 yr was 3.7–5 times greater than the unamended CON (20.8–24.3 $g \cdot kg^{-1}$ (Table 1). The mean total C concentration of the surface (0–5 cm) soil for the CM-WD and SM-WD treatments in 2016 and 2017 was significantly ($P \leq 0.05$) greater than that of the other three treatments (Table 1). The total C of the four amended treatments was 4–6-fold greater

Table 1. Legacy effects of feedlot manure treatments on total C in surface (0–5 cm) soil, water-filled pore space (WFPS) at 0–5.5 cm depth, soil temperature (0–5.5 cm depth), and soil CO_2 efflux after manure applications were discontinued for 1 (2016) and 2 (2017) yr.

	Total C		WFPS		Soil temperature		Soil CO_2 efflux	
Treatment	2016	2017	2016	2017	2016	2017	2016	2017
	$g \cdot kg^{-1}$		%		°C		$g \cdot m^{-2} \cdot h^{-1}$	
CM-ST	78.8 ± 3.1b	79.8 ± 5.6b	34.3 ± 1.9b	38.4 ± 2.8ab	21.7 ± 1.2ab	21.8 ± 0.6a	0.63 ± 0.07ab	0.40 ± 0.05a
CM-WD	122 ± 2.8a	121 ± 8.3a	26.1 ± 1.6c	33.2 ± 2.6b	18.3 ± 1.1b	22.0 ± 0.6a	0.82 ± 0.09a	0.46 ± 0.05a
CON	20.8 ± 1.0c	24.3 ± 3.3c	43.3 ± 2.2a	45.3 ± 2.7a	23.4 ± 1.2a	21.8 ± 0.6a	0.41 ± 0.05b	0.30 ± 0.03a
SM-ST	78.8 ± 3.8b	79.5 ± 6.0b	34.2 ± 2.1b	33.4 ± 2.8b	22.3 ± 1.4ab	22.3 ± 0.6a	0.72 ± 0.08a	0.43 ± 0.05a
SM-WD	118 ± 2.9a	122 ± 6.5a	26.8 ± 2.1bc	33.2 ± 2.3b	18.9 ± 1.5ab	22.2 ± 0.7a	0.86 ± 0.09a	0.46 ± 0.06a
Prob. > *F*	<0.0001	<0.0001	<0.0001	0.0036	0.021	0.93	0.0004	0.083
Estimate								
CON vs. MAN	−78.0***	−76.4***	12.9***	10.9***	3.1*	−0.3ns	−0.35***	−0.14**

Note: Values are mean ± standard error. Means within a column (and within year) not sharing a lowercase letter differ significantly at the $P < 0.05$ level. CM, composted manure; SM, stockpiled manure; ST, straw; WD, wood-chips; CON, unamended control; MAN, amended. Estimate values are negative when treatment 1 (CON, unamended control) < treatment 2 (MAN, amended), and are positive when treatments 1 > treatments 2. For example, a negative estimate value for CON vs. MAN indicates that mean value for MAN is greater than. The asterisks indicate a significant difference between treatments at $P = 0.05$ (*), $P = 0.01$ (**), and $P = 0.001$ (***).

than the unamended CON in 2016, and 3–5-fold greater than CON in 2017. Total C was significantly greater for amended than CON (pairwise comparison) in both years. There was no manure type effect on total C for the 2 yr (Table 2). Mean total C was significantly greater for WD than ST treatments by 52–53% in both years (Table 2).

Mean WFPS in 2016 was significantly greater for the unamended CON than the four amended treatments (Table 1). The WFPS in 2017 was significantly greater for unamended CON than all amended treatments except for CM-ST. The pairwise comparison revealed that WFPS was significantly greater for the unamended CON than amended treatments in both years. There was no manure type effect on WFPS in the 2 yr (Table 2). Bedding material had a significant effect on WFPS in 2016, where mean values were 29% greater for ST than WD treatment.

Mean soil temperature in 2016 was significantly greater for the CON than CM-WD treatment (Table 1). Mean soil temperatures were similar for all five treatments in 2017. Soil temperature was significantly greater for the CON than amended treatments in 2016, but mean values were similar for all five treatments in 2017 (Table 1). There was no manure type or bedding effect or their interactions on soil temperature in the 2 yr (Table 2).

Soil CO_2 efflux

Instantaneous soil CO_2 efflux values in our study ranged from 0.20 to 1.6 $g \cdot m^{-2} \cdot h^{-1}$ in 2016 and from 0.13 to 0.83 $g \cdot m^{-2} \cdot h^{-1}$ in 2017 (Fig. 1). Minimum and maximum values in 2016 occurred on May 5 and July 21, respectively; and the respective values in 2017 occurred on August 1 and July 7. Mean soil CO_2 efflux values averaged over the May 5–August 26 period in 2016 ranged from 0.41 to 0.86 $g \cdot m^{-2} \cdot h^{-1}$ for the five treatments (Table 1). Mean soil CO_2 efflux values averaged over the May 23–August 16 period in 2017 were slightly lower and ranged from 0.30 to 0.46 $g \cdot m^{-2} \cdot h^{-1}$ for the five treatments.

There was a significant ($P \leq 0.05$) treatment effect on soil CO_2 efflux in 2016 (Table 1). Soil CO_2 efflux was 1.8–2.1-fold greater for CM-WD, SM-ST, and SM-WD compared with the unamended CON. In contrast, there was no significant treatment effect on soil CO_2 efflux in 2017. The pairwise comparisons showed that CO_2 efflux was significantly greater for amended treatments compared with unamended CON in both years (Table 1). There were no significant manure type effects on CO_2 efflux in both years (Table 2). There was a significant bedding effect on CO_2 efflux in 2016, where mean values were 24% greater for WD than ST (Table 2). In contrast, there was no bedding effect in 2017. There were no significant interaction effects of type × bedding on CO_2 efflux in both years.

There were significant ($P \leq 0.05$) but weak positive correlations between CO_2 efflux and total C ($r = 0.39$, $n = 120$), WFPS ($r = 0.22$), and soil temperature ($r = 0.19$) across all treatments in 2016. In 2017, a significant and weak positive correlation occurred between CO_2 efflux and WFPS ($r = 0.38$), but not with total C ($r = 0.16$) and soil temperature ($r = 0.046$).

Discussion

The range of instantaneous soil CO_2 efflux (Fig. 1) in our study (0.13–1.6 $g \cdot m^{-2} \cdot h^{-1}$) was consistent with those in other studies. Keutgen and Huysamer (1998) reported CO_2 effluxes between 0.1 and 0.4 $g \cdot m^{-2} \cdot h^{-1}$ for soils in a

Table 2. Legacy effects of feedlot manure treatment factors on total C in surface (0–5 cm) soil, water-filled pore space (WFPS) at 0–5.5 cm depth, soil temperature (0–5.5 cm depth), and soil CO_2 efflux after manure applications were discontinued for 1 (2016) and 2 (2017) yr.

Treatment	Total C 2016	Total C 2017	WFPS 2016	WFPS 2017	Soil temperature 2016	Soil temperature 2017	Soil CO_2 efflux 2016	Soil CO_2 efflux 2017
	Prob. > *F*							
Manure type (T)	0.45	0.97	0.89	0.31	0.69	0.45	0.41	0.74
Bedding (B)	<0.0001	<0.0001	0.0001	0.31	0.95	0.91	0.046	0.40
T × B	0.45	0.94	0.85	0.35	0.86	0.78	0.79	0.82
	$g \cdot kg^{-1}$		%		°C		$g \cdot m^{-2} \cdot h^{-1}$	
SM	98.2 ± 7.7a	101 ± 9.0a	30.5 ± 1.6a	33.3 ± 1.8a	22.5 ± 0.4a	22.3 ± 0.4a	0.79 ± 0.06a	0.44 ± 0.04a
CM	100 ± 8.3a	101 ± 9.1	30.2 ± 1.4a	35.8 ± 1.9a	22.7 ± 0.4a	21.9 ± 0.4a	0.72 ± 0.06a	0.43 ± 0.04a
ST	78.8 ± 2.3b	79.6 ± 3.8b	34.2 ± 1.4a	35.9 ± 2.0a	22.6 ± 0.4a	22.0 ± 0.4a	0.68 ± 0.05b	0.42 ± 0.04a
WD	120 ± 2.0a	122 ± 4.9a	26.5 ± 1.3b	33.2 ± 1.7a	22.6 ± 0.4a	22.1 ± 0.4a	0.84 ± 0.06a	0.46 ± 0.04a

Note: Values are mean ± standard error. Means within a column (and within year) not sharing a lowercase letter differ significantly at the $P < 0.05$ level. CM, composted manure; SM, stockpiled manure; ST, straw; WD, wood-chips.

citrus orchard in South Africa. Sainju et al. (2006) reported soil CO_2 effluxes that ranged from 0.6 to 1.0 $g \cdot m^{-2} \cdot h^{-1}$ for agricultural soils in North Dakota. Pacific et al. (2008) reported CO_2 effluxes that ranged from about 0.4 to 1.0 $g \cdot m^{-2} \cdot h^{-1}$ for soils on forested hillslopes and adjacent riparian zones in Montana.

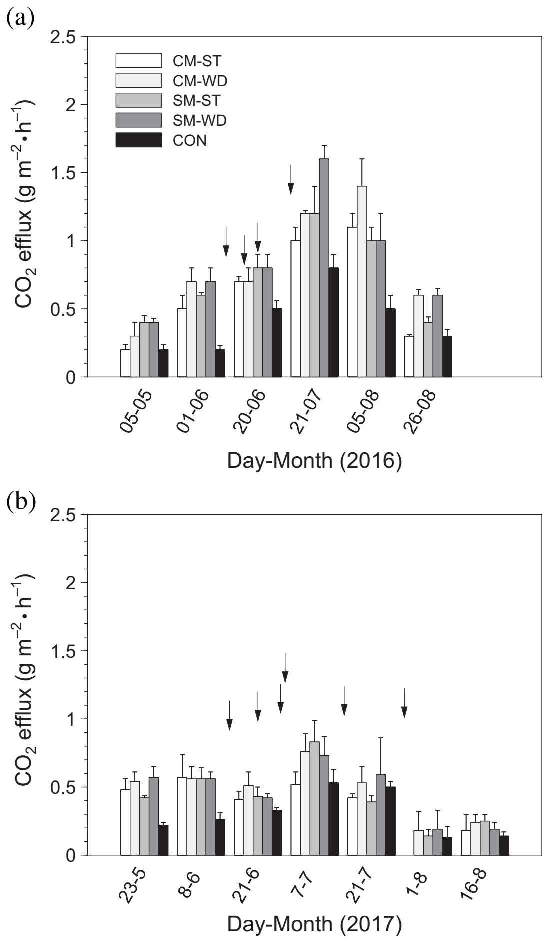
Soil CO_2 efflux increased during the growing seasons of both years and peaked at the heading stage on July 21 in 2016 and on July 7 in 2017. Others have also reported that CO_2 effluxes peaked during the growing season (Ding et al. 2007; Ellert and Janzen 2008; Heller et al. 2010; Miller et al. 2014) and attributed this to increased rhizosphere respiration during crop development.

Mean CO_2 effluxes among the four amended treatments were similar in both years and did not support our first hypothesis of short-term legacy effects for this comparison. This was consistent with previous studies that reported similar water-extractable organic C (WEOC) in the soil during 2016 for the same treatments in this study (Miller et al. 2019*b*). However, the rankings (nonsignificant) of soil CO_2 efflux for the four amended treatments in 2016 (SM-WD > CM-WD > SM-ST > CM-ST) and 2017 (SM-WD = CM-WD > SM-ST > CM-ST) were similar to total C in the amendments. Intrinsic air permeability could not explain the similar CO_2 effluxes since the surface soil amended once with these four amendments followed the ranking order SM-WD > CM-WD > CM-ST > SM-ST (Miller et al. 2000). Similar soil CO_2 efflux among the four amended treatments may have been due to the SM and CM manure types used in this study. If fresh manure had been used instead of SM, more significant differences might have been elicited by these manure types as a result of the more extreme ranges in decomposition. Ginting et al. (2003) compared soil CO_2 efflux 4 yr after the last applications of four feedlot manure amendments consisting of annual and biannual applications of fresh and composted feedlot manure. They generally reported similar soil CO_2 effluxes among the four amended treatments over five sampling dates in 1 yr (i.e., no legacy effects), which was consistent with our study.

Significantly greater CO_2 efflux for amended than unamended CON treatments (pairwise comparisons) in both years supported the second hypothesis that significant legacy effects occurred for this comparison. This finding was consistent with previous studies that reported significantly greater WEOC in soil (Miller et al. 2019*b*) for amended than unamended treatments in 2016, and also with 2× greater intrinsic air permeability for amended than unamended treatments (Miller et al. 2000). We attributed the legacy effect in our study to the 3–6-fold greater total C in the surface soil for the amended than unamended CON treatments. However, the magnitude of the CO_2 efflux difference between amended and unamended control was 8.8-fold greater in 2016 than 2017, and absolute CO_2 efflux values were generally lower in 2017 than 2016. This suggested that the legacy effect was considerably diminished between 1 and 2 yr into the legacy phase.

In contrast to our study, Ginting et al. (2003) reported similar CO_2 effluxes for four amended treatments and an unamended control 4 yr into the legacy phase. They suggested that no legacy effects on CO_2 efflux were likely due to a large native pool of soil organic matter and annual additions of carbon from plant material. A legacy effect in our study and no legacy effect in Ginting et al. (2003) study may have been due to various factors. First, our study measured CO_2 efflux 1–2 yr into the legacy phase after 17 annual applications, whereas their study was 4 yr into the legacy phase following 4 yr of annual applications. Therefore, our longer-term continuous phase and shorter legacy phase may have contributed

Fig. 1. Instantaneous soil CO_2 efflux for the five treatments and six measurement dates in 2016 and seven dates in 2017. The vertical arrows denote irrigation events. The five treatments are composted manure-straw bedding (CM-ST), composted manure-wood chip bedding (CM-WD), stockpiled manure-straw bedding (SM-ST), stockpiled manure-wood chip bedding (SM-WD), and unamended control (CON).



to significant legacy effects in our study and none in their study. Second, the silage barley crop in our study likely contributed to lower inputs of organic C from crop residue than the corn crop used in their study. Third, other geographic, environmental, and land use factors may have contributed to differences in legacy effects in these two studies.

The total C of our unamended surface soil in 2016 (20.8 $g \cdot kg^{-1}$) and 2017 (24.3 $g \cdot kg^{-1}$) was similar to 19.3 $g \cdot kg^{-1}$ in Eghball et al.'s (2004) study. We estimated the total C returned to the soil in our amended and CON treatments using the dry matter yields of barley in 2016 and 2017 (6.0–7.9 $Mg \cdot ha^{-1}$). We also used a relative annual plant C allocation coefficient (0.21) for barley where all the surface residue is removed (whole barley plant harvested for silage) and total C content of 0.45 $g\ C \cdot g^{-1}$ for grain crops (Bolinder et al. 2007). The total C returned to our soil from plant material (standing stubble, including roots) was estimated to be 0.6–0.7 $Mg\ C \cdot ha^{-1}$ for the amended and unamended treatments. As expected, our values for C returned from the barley crop were considerably lower than the value of >4.1 $Mg\ C \cdot ha^{-1} \cdot y^{-1}$ reported for corn (Ginting et al. 2003). Therefore, these low C inputs from barley stubble to soil may not have masked the legacy effects of manure in our study as compared with the much higher C returns in Ginting et al.'s (2003) study.

Some studies have suggested that greater osmotic potential or soil salinity caused by higher application rates of manure may reduce soil CO_2 efflux (Gregorich et al. 1998; Mavi and Marschner 2017). We did not measure the electrical conductivity (EC) of the surface soil in 2016 and 2017. However, after 15 annual applications of manure, the EC of the surface soil was 0.8 $dS \cdot m^{-1}$ for the CON and ranged from 1.7 to 7.0 $dS \cdot m^{-1}$ for the amended treatments (Miller et al. 2017). Although these EC values for amended treatments would likely have increased the soil osmotic potential during the legacy phase, soil respiration was still significantly greater for the amended than unamended treatments. Zhang et al. (2018) reported that soils without feedlot manure for 13 yr (following 30 annual applications) had significantly different soil microbial communities compared with unamended and fertilized treatments. Therefore, the soil microbial communities found under long-term manure application for our study may have evolved to adapt to the higher osmotic potential of the manured soils. Greater CO_2 efflux for amended than unamended CON treatments emissions may negate some of the beneficial effects of manure on soil properties (Heller et al. 2010).

No significant effect of manure type on soil CO_2 efflux in both years led us to reject the hypothesis of greater efflux for SM than CM. This finding was not consistent with greater total C of SM than CM amendments (Larney et al. 2006; Miller et al. 2009). However, it was consistent with similar total soil C for SM and CM treatments in 2016 and 2017, with similar WEOC concentrations in the surface soil for SM and CM treatments at the same application rate (77 $Mg \cdot ha^{-1}$) during 2016 (Miller et al. 2019b) and with similar intrinsic air permeability of the soil (Miller et al. 2000). Different total C contents in the soil than amendments were likely caused by dilution of the amendment when it was incorporated into the soil. As discussed earlier, we may have elicited more manure type effects if we had compared fresh and composted manure instead of using stockpiled manure. Ginting et al. (2003) also reported similar soil CO_2 effluxes from soils amended with fresh manure or composted feedlot manure during the legacy phase.

Significantly greater CO_2 efflux for WD than ST in 2016 (but not 2017) supported the hypothesis of greater efflux for this bedding material for this year and also suggested diminishing legacy effects over a short period of time. This was consistent with greater total C in WD than ST amendment (Larney et al. 2008; Miller et al. 2009). Miller et al. (2019*b*) also reported significantly greater WEOC in surface soil for WD than ST at 77 Mg·ha^{-1} in 2016. Miller et al. (2014) also reported greater soil CO_2 efflux for WD than ST at 77 Mg·ha^{-1} for some sampling dates after 13–14 yr of annual applications. They speculated that greater soil respiration for WD than ST may have been due to greater aeration of soil caused by larger particles of undecomposed wood chips. This was consistent with Miller et al. (2000), who reported 1.8 times greater intrinsic air permeability for surface soil amended with WD than ST. In addition, the greater C/N ratio of soil for WD than ST (Miller et al. 2014) may have contributed to greater CO_2 efflux. Emissions of CO_2 have been found to correlate positively with C/N ratio (Oertel et al. 2016).

Total soil C explained 16–39% of the CO_2 efflux variation in both years. Gregorich et al. (1998) reported that soil organic C only explained 3% of the variation in CO_2 efflux after 2 yr of annual applications of solid dairy manure. Miller et al. (2014) reported that soil organic C explained 35% of the variation in CO_2 efflux for stockpiled feedlot manure with WD or ST bedding at 77 Mg·ha^{-1}, while water-soluble C and N had no effect on CO_2 efflux.

The WFPS explained 22–38% of the variation in CO_2 efflux. The WFPS was significantly lower for the amended treatments than unamended CON because the soil bulk density was lower and total porosity greater for amended treatments. Increases in volumetric soil water content from organic amendments are often small or negligible because the increased gravimetric water content is offset by decreased soil bulk density (Khaleel et al. 1981). Although WFPS was lower for amended than unamended CON, the reverse trend was found for gravimetric soil water content (data not shown).

The positive influence of soil moisture on soil respiration has been attributed to the rise in microbial population and activity (Rochette et al. 1991). Some researchers have reported a positive effect of WFPS or soil moisture on soil CO_2 efflux (Akinremi et al. 1999), but it was not the dominant factor (Liebig et al. 1995; Heller et al. 2010; Miller et al. 2014), or it depended on the WFPS level and interaction with soil temperature (Ding et al. 2007). Carbon dioxide production increased with increasing WFPS up to a maximum at 85% WFPS in an incubation study with three soils of varying textures (Zhang et al., 2004). Others found no significant effect of WFPS or soil moisture on soil CO_2 efflux (Kowalenko et al. 1978; Paul et al. 1999; Bajracharya et al. 2000).

Soil temperature explained 5–19% of the variation in CO_2 efflux in our study. Ginting et al. (2003) reported no correlation of soil temperature with CO_2 efflux during the growing season when root growth masked soil temperature effects, but soil temperature explained 9% of the variation during the nongrowing season. Miller et al. (2014) reported that soil temperature explained 8% of the variation in CO_2 efflux after 13–14 yr of annual applications of stockpiled feedlot manure with WD or ST bedding at 77 Mg·ha^{-1}. In contrast, Gregorich et al. (1998) reported that soil temperature explained 44–56% of the variation in CO_2 efflux after 2 yr of annual dairy manure application.

Conclusions

Soil CO_2 efflux was similar among the four amended treatments for both years. Soil CO_2 efflux was greater for amended than unamended treatments in both years, but the legacy effect was diminished from 1–2 yr after manure applications were stopped. Soil CO_2 efflux was similar for SM and CM and was greater for WD than ST in 2016 but not 2017. Overall, long-term manure application has the potential to create short-term legacy effects on soil CO_2 efflux, but whether or not this potential is expressed likely depends on the temporal dynamics of soil, plant, climate, and environmental factors. Future research needs to study the longer-term legacy effects of these feedlot manure amendments on soil cumulative CO_2 efflux, as well as possible relationship of water-soluble C, soil salinity, and other soil properties to CO_2 efflux.

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