

Short-term carbon dioxide emission under contrasting soil disturbance levels and organic amendments



Roberto André Grave^a, Rodrigo da Silveira Nicoloso^{b,*}, Paulo Cezar Cassol^c, Celso Aita^d, Juliano Corulli Corrêa^b, Morgana Dalla Costa^b, Diego Daniel Fritz^b

^a Catarinense Federal Institute of Education, Science and Technology (IFC), 89700-000 Concórdia, SC, Brazil

^b Embrapa Swine and Poultry, 89700-000 Concórdia, SC, Brazil

^c Santa Catarina State University (UDESC), 88035-001 Lages, SC, Brazil

^d Federal University of Santa Maria (UFSM), 97119-900 Santa Maria, SC, Brazil

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ABSTRACT

Agriculture can be either a source or sink of atmospheric CO₂ depending on soil management. The application of swine slurry in conventional tilled soils could enhance soil CO₂ emission depleting soil organic C stocks. However, the use of recalcitrant C-rich organic fertilizers in no-till soils can offset soil CO₂ emission promoting soil C sequestration. This hypothesis was tested by evaluating short-term CO₂-C emissions from a Rhodic Nitisol under contrasting soil disturbance levels (disturbed (DS) and undisturbed soil (US)) top-dressed with mineral or organic fertilizers (urea (UR), raw swine slurry (RS), anaerobically digested swine slurry (ADS), and composted swine slurry (CS)). Soil CO₂ emission was evaluated for 64 days using static chambers where gas samples were collected and analysed by photoacoustic infrared spectroscopy. Soil water-filled pore space (WFPS), temperature and meteorological data were concomitantly registered and a first-order exponential decay model was used to assess the decomposition of organic fertilizers and CO₂ emissions induced by soil disturbance. Soil CO₂-C emission was correlated with soil temperature, while limiting soil aeration impaired CO₂-C efflux when WFPS > 0.6 cm³ cm⁻³. Disturbance increased soil CO₂-C efflux (36.3 ± 2.2 kg CO₂-C ha⁻¹ day⁻¹) in relation to US (33.3 ± 1.6 kg CO₂-C ha⁻¹ day⁻¹). Extra labile C input through RS amendment induced an increased soil CO₂-C efflux for a longer period ($t_{1/2}$ = 16.9 and 9.6 days in DS and US treatments, respectively), resulting in higher CO₂-C emissions than soil amended with other fertilizers. The recalcitrant C input by ADS and CS had limited effect on soil CO₂-C emissions. CS presented a genuine potential for substantial soil organic C accumulation while offsetting increased CO₂-C emissions in comparison to RS amended soils.

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1. Introduction

Brazil is the fourth largest swine producer and exporter in the world, with a herd of 38.6 million heads in 2013 (USDA-FAS, 2014). The annual swine slurry production in Brazil was estimated as 122 million cubic meters containing approximately 3.4 × 10⁵ Mg of N, 2.9 × 10⁵ Mg of P₂O₅, and 1.8 × 10⁵ Mg of K₂O and accounts for 9.4, 6.8, and 3.7% of the demand for these nutrients by Brazilian agriculture, respectively (Aita et al., 2014a). The use of swine slurry as fertilizer in agricultural soils has been the usual fate of this waste

in Brazil (Kunz et al., 2009) and is an important strategy for sustainable concentrated animal feeding operations (Kunz et al., 2005) that supply lower cost nutrients for crop production instead of mineral fertilizers.

Although incorporation (Rochette et al., 2009) or injection (Aita et al., 2014b) of ammonia-rich swine slurry into the soil would be preferable to prevent NH₃-N volatilization, swine slurry topdressing remains the usual practice in Brazilian no-till system. These practices can impact soil C and N dynamics by affecting soil CO₂ emissions (Aita et al., 2012). Increased soil CO₂ emission can be observed after soil tillage operations which incorporate crop residues into soil (Reicosky and Lindstrom, 1993; Reicosky et al., 1997). Soil amendment with organic residues or mineral fertilizers can also impact C and N dynamics and promote increases in soil CO₂ emissions (Chantigny et al., 2001, 2002; Aita et al., 2012). However, studies assessing the contribution of organic and mineral amendments on soil CO₂ emission present contrasting results in

* Corresponding author at: Caixa Postal 21, 89700-000 Concórdia, SC, Brazil. Tel.: +55 49 34410400; fax: +55 49 34410497.

E-mail addresses: roberto.grave@ifc-concordia.edu.br (R.A. Grave), rodrigo.nicoloso@embrapa.br (R.d.S. Nicoloso), a2pc@cav.udesc.br (P.C. Cassol), celsoaita@gmail.com (C. Aita), juliano.correa@embrapa.br (J.C. Corrêa), morgadc@hotmail.com (M.D. Costa), fritzdf@hotmail.com (D.D. Fritz).

the literature. While some studies reported increased mineralization of crop residues-C and enhanced soil CO₂ emissions (Chantigny et al., 2001; Muhammad et al., 2011), others reported no synergistic effect when crop residues are incorporated (Giacomini and Aita, 2008; Aita et al., 2012). When N is limiting, swine slurry amendment could enhance crop residue decomposition, however, this effect would not be expected if the original concentrations of soil mineral N or the mineralization of soil organic N are sufficient to support the decomposition of crop residues (Aita et al., 2012).

Modifications of swine slurry organic matter quality via anaerobic digestion or composting (Vivan et al., 2010; Angnes et al., 2013) could also impact C and N dynamics and potentially decrease CO₂ emissions from soils amended with these materials (Bertora et al., 2008; Giacomini and Aita, 2008; Marcato et al., 2009; Yang et al., 2002). Soil CO₂ emission peaks are promoted by the presence of carbonates in the swine slurry which can be released when applied to acidic soils (Chantigny et al., 2002) and also by the rapid mineralization of volatile fatty acids (labile C) found in swine slurry (Kirchmann and Lundvall, 1993). Labile C forms are promptly consumed during swine slurry treatment (Vivan et al., 2010; Angnes et al., 2013) resulting in recalcitrant C-rich organic fertilizers. However, literature results are still inconclusive regarding CO₂ emission from soils amended with swine slurry treated by anaerobic digestion or composting; this is important since these are emerging manure treatment technologies in Brazil (Kunz et al., 2009).

Although some studies reported lower CO₂ emission from soils amended with composted or anaerobically digested swine slurry in comparison to raw swine slurry (Yang et al., 2002; Marcato et al., 2009), others found no differences in emissions between composted and raw swine slurry amendments in conventional or no-till systems (Giacomini and Aita, 2008) or between anaerobically digested and raw swine slurry in soil incubation experiments (Bertora et al., 2008). Nonetheless, soil amendment with composted organic residues in no-tillage system is generally reported to substantially increase soil organic C stocks by offsetting soil CO₂-C emissions (Gulde et al., 2008; Lal, 2009; Nicoloso, 2009; Powlson et al., 2012). Anaerobic digestion and composting could also offset CH₄ emission in relation to conventional swine slurry management and storage (Kunz et al., 2009; Zhong et al., 2013) and mitigate soil N₂O emission in relation to other organic residues (Zhong et al., 2013).

The assessment of short-term CO₂ emissions (8–90 days) is useful to estimate emissions from tillage operations during the mineralization of organic carbon in soil as well as from the decomposition of crop and other organic residues (La Scala et al., 2006; Aita et al., 2008; Drewitt et al., 2009; Pes et al., 2011; Aita et al., 2012). Thus, in this study CO₂ emission from a Nitisol in southern Brazil was assessed for over 64 days in order to infer

impacts of contrasting soil disturbance levels on the decomposition of organic fertilizers. We also hypothesized that application of recalcitrant C-rich organic fertilizers (anaerobically digested or composted swine slurry) on undisturbed soils (no-till) can decrease soil CO₂-C emission in relation to disturbed soils (conventional tillage) amended with raw swine slurry or urea thereby promoting soil C sequestration.

2. Materials and methods

2.1. Field experiment

The experiment was initiated in January 2013 on a Rhodic Nitisol (FAO, 1998) located in Concordia-SC, Brazil (27°18'53"S, 51°59'25"O). The site had been cultivated with maize and wheat crops under no-tillage. The soil characteristics (0–0.10 m soil layer) were: clay, silt and sand content of 250, 460, and 290 g kg⁻¹, respectively, pH-H₂O_(1:1) 5.3, pH-SMP 5.8, SOM 39.0 g kg⁻¹, P_{Mehlich-1} 6.6 mg dm⁻³, K_{Mehlich-1} 249.6 mg dm⁻³, Ca 7.5 cmol_c dm⁻³, Mg 3.3 cmol_c dm⁻³, CTC 11.8 cmol_c dm⁻³ and base saturation 68%. The local climate is humid subtropical (Cfa) based on the Köppen classification system (EMBRAPA, 2004).

The experiment had a split-plot design with two soil disturbance levels as the main plots (1 m × 5 m) and five fertilization treatments as the subplots (1 m × 1 m). All treatments were replicated four times. The buffer rows measured 1 m between replication blocks and 0.4 m among plots and subplots. Existing plant residues were manually removed and 4 Mg ha⁻¹ of wheat straw (*Triticum aestivum* (L.)) was placed on the soil surface of each subplot (January 23rd: day 0). The soil disturbance treatments were: undisturbed (US) and disturbed soil (DS). In the DS treatment, the wheat straw was incorporated in the 0–0.10 m layer manually with a shovel, ensuring that no aggregates >2 cm remained intact (January 25th: day 2). In the US treatment, the wheat straw was maintained at the soil surface with no disturbance. On day 5 (January 28th) the subplot fertilization treatments were established by manual surface application of 140 kg total-N ha⁻¹ as either urea (UR), raw swine slurry (RS), anaerobically digested swine slurry (ADS), or composted swine slurry (CS); control treatment (CTR) received no fertilizer. The nitrogen fertilization rate followed the CQFS RS/SC (2004) guidelines with a goal of 9 Mg ha⁻¹ of maize grain yield. Varying C inputs among treatments were related to composition variation of organic fertilizers used in this study; material was obtained from a fattening swine farm at Embrapa Swine and Poultry Research Center (Table 1). The RS was collected from deep storage tanks, while the ADS was collected from an anaerobic lagoon composed of effluent from a covered lagoon biodigester used to treat swine slurry (Vivan et al., 2010). The CS consisted of a mixture of swine slurry with sawdust and wood shavings (bulking agents) which was composted for 150 days as reported by Angnes et al., 2013. Samples of wheat straw, RS,

Table 1
Application rate and characteristics of the wheat straw and organic fertilizers used in this study.

Material	Characteristics								Application rate	TOC input	TN input
	DM	VS	TOC	TN	Org-N	NH ₄ -N	NO ₃ -N	C/N			
RS ^a	%	kg m ⁻³							m ³ ha ⁻¹	kg ha ⁻¹	kg ha ⁻¹
ADS ^a	7.4	45.9	29.0	4.4	1.7	2.7	ND	6.6	31.7	919	140
CS ^b	6.5	38.4	17.7	5.2	2.6	2.6	ND	3.4	27.1	480	140
WS ^b		g kg ⁻¹							Mg ha ⁻¹		
CS ^b	29.1	ND	317.0	16.6	15.1	1.2	0.3	19.1	29.0	2,675	140
WS ^b	90.0	ND	428.7	12.2	ND	ND	ND	35.1	4.0	1,543	44

RS: raw swine slurry; ADS: anaerobically digested swine slurry; CS: composted swine slurry; WS: wheat straw; ND: not determined; DM: dry matter; VS: volatile solids; TOC: total organic carbon; TN: total nitrogen; Org-N: organic nitrogen; NH₄-N: ammonium-nitrogen; NO₃-N: nitrate-nitrogen; C/N: total organic carbon/total nitrogen ratio.

^a Results are expressed on a fresh matter basis.

^b Results are expressed on a dry matter basis.

ADS, and CS were analysed for characterization of these materials as reported by Angnes et al., 2013.

2.2. Gas sampling and analysis

The experiment was conducted for 64 days starting on January 23rd (day 0) when the wheat straw was added to the plots. Gas samplings started on January 24th (day 1) and were performed daily for the first 30 days and at least every other day afterwards. Air was sampled from static chambers (0.4 m × 0.8 m × 0.3 m (L × W × H)) mounted over a base (0.09 m high) inserted 0.06 m into the soil. The headspace volume of the chambers averaged 105.6 L. The chambers were equipped with three internal fans to homogenize the internal atmosphere, a probe thermometer for monitoring the chamber air temperature, and a rubber septum from which air samples were taken through a plastic tube closed by a three-way “luer-lock” valve.

Air was sampled between 10:00 and 12:00 h. Chambers were closed and sealed with water to avoid air exchange between the chamber and the atmosphere. Time zero samples were collected outside the chamber, while the samples from the chamber atmosphere were collected after 15, 30, and 45 min. The chamber fans were activated for only 30 s prior to sample collection to minimize bias in CO₂ efflux resulting from forced convection of the internal atmosphere of the chambers. The samples were collected with a set of two 60 mL polypropylene syringes united by three-way “luer-lock” valves, totaling 120 mL of sampling volume. The syringes were stored in a cooler and analysed within 3 h after collection. The samples were injected in an INNOVA 1412 gas analyser (Lumasense Technologies, Denmark) where the content of CO₂ in the air samples was assessed by photoacoustic infrared spectroscopy (Yamulki and Jarvis, 1999; Nicoloso et al., 2013).

The soil CO₂-C fluxes were calculated based on the following equations:

$$Q = \frac{(C \times \text{MMR} \times P \times V)}{(R \times T)} \quad (1)$$

$$f = \frac{(\Delta Q / \Delta t)}{A} \quad (2)$$

where Q is the mass of CO₂-C inside chamber ($\mu\text{g CO}_2\text{-C}$); C is the content of CO₂ in the sample measured by the gas analyser ($\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ air}$); MMR is the molecular mass ratio of CO₂ to CO₂-C ($12 \mu\text{g C } \mu\text{mol}^{-1} \text{ CO}_2$); P is partial gas pressure (assumed as 1 atm); V is the volume of the chamber (L); R is the ideal gas constant ($0.0821 \text{ atm L mol}^{-1} \text{ K}^{-1}$); T is the gas temperature (K); f is the CO₂-C flux ($\mu\text{g CO}_2\text{-C m}^{-2} \text{ min}^{-1}$); ΔQ is the linear change on the CO₂ content ($\mu\text{g CO}_2\text{-C}$) inside chamber over time ($\Delta t, \text{ min}^{-1}$); and A is the basal area of the chamber (m^2). The results were then extrapolated to a daily basis (Chatskikh and Olesen, 2007; Chaves et al., 2009; Pes et al., 2011).

2.3. Meteorological data and soil abiotic factors

Precipitation, mean daily air temperature, and humidity were recorded at a meteorological station located 250 m from the experimental area. Soil temperature was measured at the time of samplings with digital temperature probes inserted in the 0–0.10 m soil layer of each subplot. Soil water content was assessed on a regular basis (2–3 times a week) by sampling the 0–0.10 m soil layer from each subplot. Subsamples were weighed and dried at 105 °C until constant mass to determinate the soil gravimetric water content ($w, \text{ g g}^{-1}$).

At the end of the evaluation period, undisturbed soil samples were collected from 0–0.05 and 0.05–0.10 m soil layers from each subplot with steel cylinders (0.05 m × 0.05 m; height × diameter). Nylon screens were attached to the bottom of the cylinders to prevent soil loss. The soil samples within cylinders were saturated with water for 48 h, weighed and dried at 105 °C, and weighed again until constant mass to determinate the soil bulk density (BD, g cm^{-3}). Soil total porosity was calculated according to the following equation:

$$TP = \frac{(M_s - M_d) / \rho}{V} \quad (3)$$

where TP is the soil total porosity ($\text{cm}^3 \text{ cm}^{-3}$); M_s is the mass of the water-saturated soil sample (g); M_d is the mass of the dry soil sample (g); ρ is the density of water (assumed as 1 g cm^{-3}), and V is the volume of the cylinder (cm^3).

The water-filled pore space (WFPS, $\text{cm}^3 \text{ cm}^{-3}$) was then calculated according to the following equation:

$$\text{WFPS} = \frac{w \times \text{BD} / \rho}{TP} \quad (4)$$

2.4. Analysis of CO₂-C emissions

The effect of soil disturbance and fertilization treatments on soil CO₂-C emissions was assessed using the approach described by Pes et al., 2011. Briefly, the effect of fertilization was assessed by the differences of daily soil CO₂-C emissions between treatments which received fertilization (UR, RS, ADS, and CS) in relation to CTR within US and DS treatments. This approach was applied to estimate the decomposition rate of crop residues and organic fertilizers under contrasting soil disturbance levels. Also, the differences between DS and US treatments were used to infer the effect of soil disturbance on increasing soil CO₂-C effluxes.

A first-order exponential decay model was applied to describe the differential CO₂-C fluxes between contrasting treatments (La Scala et al., 2008):

$$\Delta f(t) = C_0 k \times e^{-kt} \quad (5)$$

where Δf is the difference in daily soil CO₂-C fluxes between contrasting treatments ($\text{kg CO}_2\text{-C ha}^{-1} \text{ day}^{-1}$) at a given time (t , days after fertilizer application); C_0 is the estimated labile carbon content from soil organic matter, wheat straw, and organic fertilizers added to the soil available for decomposition (kg ha^{-1}); k is the carbon decay rate (day^{-1}); and e is the base of the natural logarithm.

The half-life ($t_{1/2}$) of increased CO₂-C emissions promoted by soil disturbance or fertilizers was calculated by the given equation:

$$t_{1/2} = \frac{\ln(2)}{k} \quad (6)$$

where $\ln(2)$ is the natural logarithm of 2; and k is the carbon decay rate (day^{-1}) determined by the first-order exponential decay model adjusted to the data.

2.5. Statistical analysis

Soil temperature, WFPS, daily and cumulative CO₂-C emissions data were submitted to analysis of variance (ANOVA) and treatments means were compared using the Fisher's LSD test. Correlations between soil abiotic factors, meteorological data and soil CO₂-C emissions were evaluated using Pearson's coefficient (r). Non-linear regression analysis was applied to test the adjustment of the first-order exponential decay model to the differential CO₂-C fluxes between contrasting treatments and the significance of the

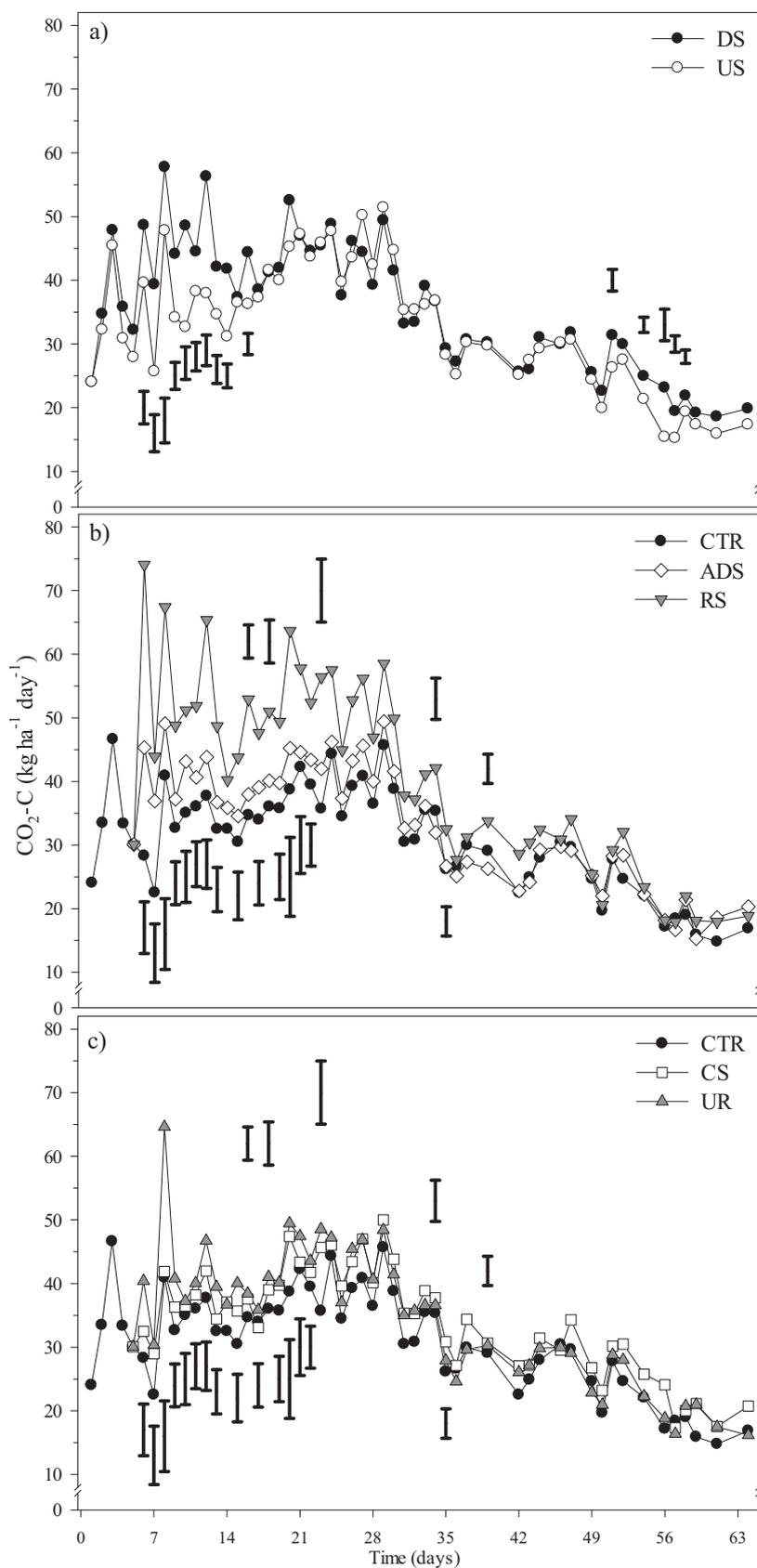


Fig. 1. Soil CO₂-C emissions according to the main effects of soil disturbance (a) and fertilization treatments (b,c). DS: disturbed soil; US: undisturbed soil; CTR: control without fertilization; UR: urea; RS: raw swine slurry; ADS: anaerobically digested swine slurry; CS: composted swine slurry. Means separation bars denote the Fisher's test LSD ($p < 0.05$).

C_0k and k values estimated by the mathematical model. All statistical analyses were performed by utilizing the software SigmaPlot 12.5 (Systat Software Inc.) and results were considered statistically significant at $p < 0.05$.

3. Results and discussion

3.1. Soil abiotic factors and daily CO_2 -C emission

No interaction between soil disturbance and fertilization treatments was detected, thus, the results presented in Fig. 1 and the following discussion address the main effects of soil disturbance (Fig. 1a) and fertilization (Fig. 1b–c) on soil CO_2 -C efflux. Soil CO_2 -C emission (Fig. 1) showed wide variation from 14.8 ± 1.3 (mean \pm s.e.) to 74.1 ± 3.3 $kg\ ha^{-1}\ day^{-1}$ and were markedly affected by soil abiotic factors and environment. Increasing rainfall during the experiment was followed by a decrease in ambient air and soil temperature and an increase in WFPS (Fig. 2). No differences in soil temperatures were seen among the evaluated treatments (Fig. 2c–d), however, soil WFPS was consistently higher for US than DS (Fig. 2a). The presence of crop residues on the soil surface could have enhanced rainfall water infiltration and decreased evapotranspiration in US treatments, while surface sealing of the topsoil layer could have impaired water infiltration in DS treatments (Lanzanova et al., 2010).

Soil temperature was the main abiotic factor driving CO_2 -C emissions, corroborating previous findings (Drewitt et al., 2009;

Pes et al., 2011). Ambient air and soil temperature had positive linear correlations (data not shown) with CO_2 -C emissions ($r=0.486$ and $p < 0.001$; $r=0.659$ and $p < 0.001$; respectively), while ambient humidity and the WFPS had negative relationships ($r=-0.110$ and $p=0.014$; $r=-0.191$ and $p=0.004$; respectively). Higher CO_2 -C emissions would be expected with increases in soil water content (Pes et al., 2011), however, limiting soil aeration conditions (WFPS $> 0.6\ cm^3\ cm^{-3}$, Linn and Doran, 1984) associated with decreasing soil temperatures in the second half of the evaluation period limited the emission rates.

Soil disturbance and crop residue incorporation promoted a limited but noticeable increase in CO_2 -C emission. Mean soil CO_2 -C efflux for the DS treatment ($36.3 \pm 2.2\ kg\ CO_2\text{-C}\ ha^{-1}\ day^{-1}$) was only 9.0% higher than the average CO_2 -C emission efflux from the US treatment ($33.3 \pm 1.6\ kg\ CO_2\text{-C}\ ha^{-1}\ day^{-1}$) during the whole experimental period (Fig. 1a). The incorporation of crop residues into soil enhanced soil CO_2 -C efflux in comparison to US, yet this effect was less pronounced in our study when compared to literature findings (Reicosky, 1997; La Scala et al., 2006; Pes et al., 2011). Pes et al., 2011 reported no differences in CO_2 -C emissions between conventional tillage and no-till from a Brazilian clayey Ferralsol when crop residues were removed. However, when crop residues were present, CO_2 -C emission from conventional tillage was 71.8% higher than no-till. In the DS treatment (Fig 2a), lower soil water content and strong organomineral interactions stabilized organic C leading to decreased residue decomposition (Grandière et al., 2007; Razafimbelo et al., 2008) which may have limited CO_2 -C emissions due to soil disturbance.

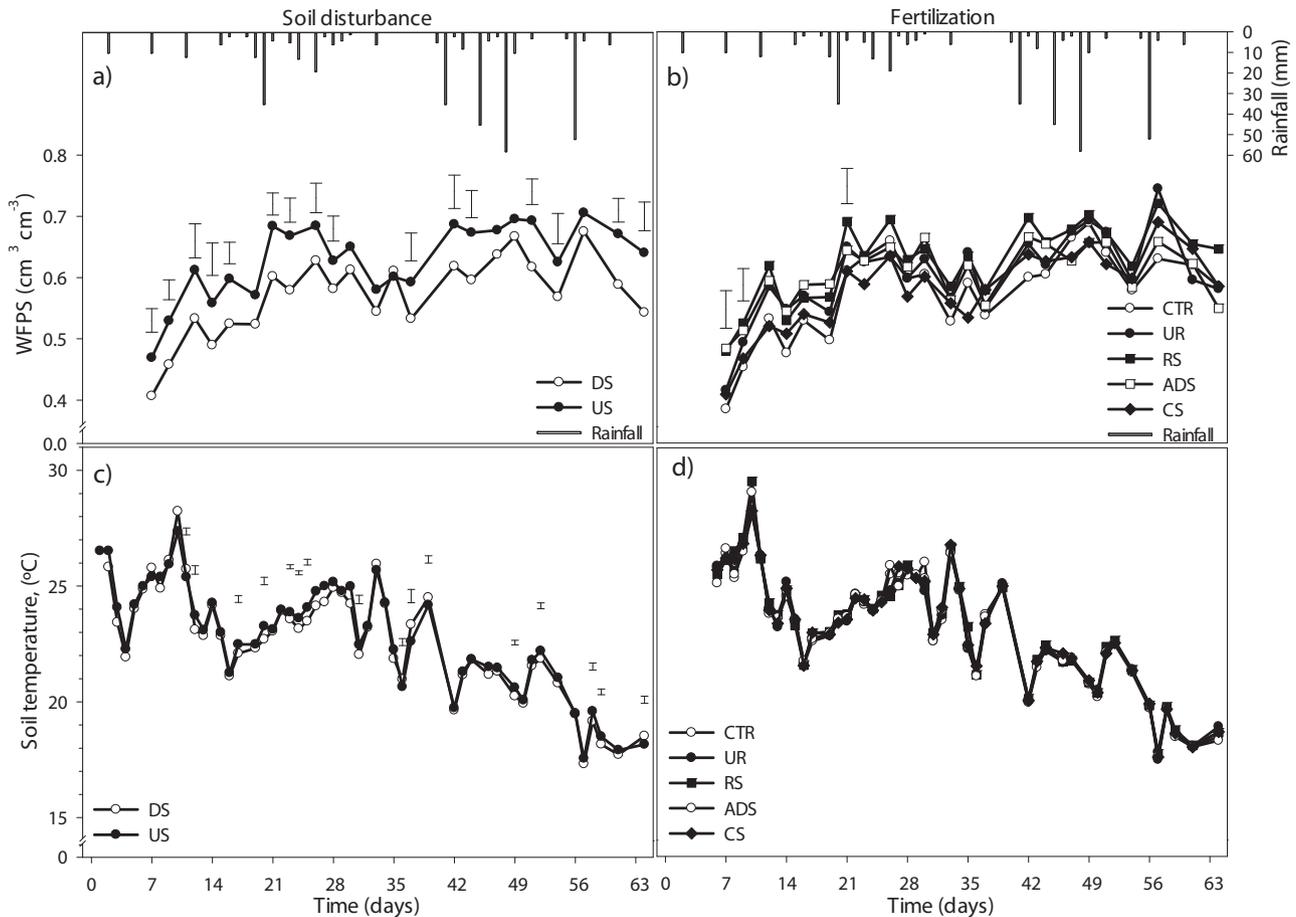


Fig. 2. Water-filled pore space (WFPS) (a,b) and temperature (c,d) in the 0–0.10 m soil layer according to soil disturbance (a,c) and fertilization treatments (b,d). DS: disturbed soil; US: undisturbed soil; CTR: control without fertilization; UR: urea; RS: raw swine slurry; ADS: anaerobically digested swine slurry; CS: composted swine slurry. Vertical bars denote the rainfall registered during the experiment. Means separation bars denote the Fisher's test LSD ($p < 0.05$).

Nonetheless, the effect of fertilization treatments on soil CO₂-C emissions were more pronounced and remained significant for up to 18 days after fertilizer application (Fig. 1b-c). Daily CO₂-C efflux from the RS treatment was consistently higher than other treatments (CTR, UR, ADS, and CS). The RS has a higher proportion of labile C, as expressed by lower C/N ratio and higher volatile solids (VS), mineral N (Table 1) and carbonate content than the other tested organic fertilizers (Kirchmann and Lundvall, 1993; Chantigny et al., 2002; Giacomini and Aita, 2008; Vivan et al., 2010; Angnes et al., 2013). Thus, increased soil CO₂-C emission from the RS treatment was related to increased decomposition of crop residues (Chantigny et al., 2001) and slurry-added C (Aita et al., 2008), and/or by inorganic CO₂-C emission from slurry-derived carbonate released in this acidic soil (Chantigny et al., 2002).

CO₂-C efflux from soil amended with UR, ADS, and CS were also higher than the CTR treatment (Fig. 1b-c). The higher mineral N input (UR > ADS > CS, Table 1) increased by the same proportion as the mineral N content (NH₄⁺-N + NO₃⁻-N, data not shown) in the soil surface layer (0–0.10 m). This higher availability of mineral N probably enhanced the decomposition of soil organic C and crop residues, favoring CO₂-C emissions from these treatments during the first days after fertilizer amendment (Chantigny et al., 2001; Aita et al., 2008; Giacomini and Aita, 2008). Afterwards, the consumption of labile and readily mineralizable C pools, N displacement from the zone of decomposition (i.e., crop residues and organic fertilizers, Aita et al., 2008), limitations to aerobic microbial activity due to restricting soil aeration (WFPS > 0.6 cm³ cm⁻³), and decreasing soil temperature (Fig. 2) would have impaired CO₂-C emissions from these treatments.

3.2. CO₂-C emission induced by organic fertilizers

The first-order exponential decay model (La Scala et al., 2008) was fitted to the differential soil CO₂-C emissions from contrasting fertilization treatments using the CTR treatment as the baseline under the same soil disturbance level (Fig. 3). This approach was used to estimate decomposition of organic fertilizers and the effect of mineral fertilization on decomposition of crop residues under contrasting soil disturbance levels. Amendment of DS with UR and ADS promoted a similar increase in soil CO₂-C emission compared to the CTR treatment with estimated C decay rates of 0.061 ± 0.015

($p < 0.01$) and 0.065 ± 0.015 day⁻¹ ($p < 0.01$), resulting in half-lives of 11.4 and 10.7 days, respectively (Fig. 3a). Under DS, RS promoted higher differential CO₂-C emission with a lower C decay rate (0.041 ± 0.006 day⁻¹, $p < 0.01$) and longer half-life (16.9 days). These results indicate that the mineral nitrogen input provided by the ADS (70 kg NH₄⁺-N ha⁻¹) was enough to stimulate the mineralization of crop residues-derived C, as verified in the UR treatment (140 kg NH₄⁺-N ha⁻¹) (Muhammad et al., 2011) without adding extra labile C or carbonates to enhance soil CO₂-C emissions as noted in the RS treatment (85 kg NH₄⁺-N ha⁻¹). Thus, soil amended with ADS decreased soil CO₂-C emissions in relation to RS. This result is in agreement with previous findings (Marcato et al., 2009). Nonetheless, the differential CO₂-C emission from CS amended soil remained low and stable during the whole evaluation period, averaging 3.1 ± 1.1 kg CO₂-C ha⁻¹ day⁻¹. This result indicates a very discrete mineralization of CS-added C to the soil. The complete oxidation of labile C pools and progressive humification of the swine slurry and sawdust mixture during the composting process (Angnes et al., 2013) resulted in a highly recalcitrant organic fertilizer which promotes lower CO₂-C emissions and potentially results in soil organic carbon accumulation in CS amended soils.

It is well known that organic fertilization can increase soil organic C stocks (Gulde et al., 2008; Nicoloso, 2009; Powlson et al., 2012). However, a recent study associated soil organic C accumulation and saturation to increased C input quantity (not quality) in a Chernozem soil amended with solid beef cattle manure (Carrington et al., 2012). Our results suggest otherwise since the decomposition of organic fertilizers in the soil were affected by previous manure treatment (Fig. 3). In order to achieve the same N fertilization rate recommended for a maize crop (CQFS RS/SC, 2004), C input by RS, ADS, and CS were 919, 480, and 2675 kg ha⁻¹, respectively. Cumulative soil CO₂-C emissions (ΔCO₂-C) from DS fertilized with UR, RS, ADS, and CS were 233, 733, 231, and 185 kg ha⁻¹ higher than DS+CTR treatment, respectively (Fig. 3a). However, using the treatment DS+UR as a reference to isolate the effect of C input through organic amendments in relation to mineral nitrogen fertilization (UR), soil CO₂-C emissions promoted by organic fertilizers were 500 kg ha⁻¹ higher in the DS+RS treatment, but 2 and 48 kg ha⁻¹ lower in the DS+ADS and DS+CS treatments, respectively. After 64 days,

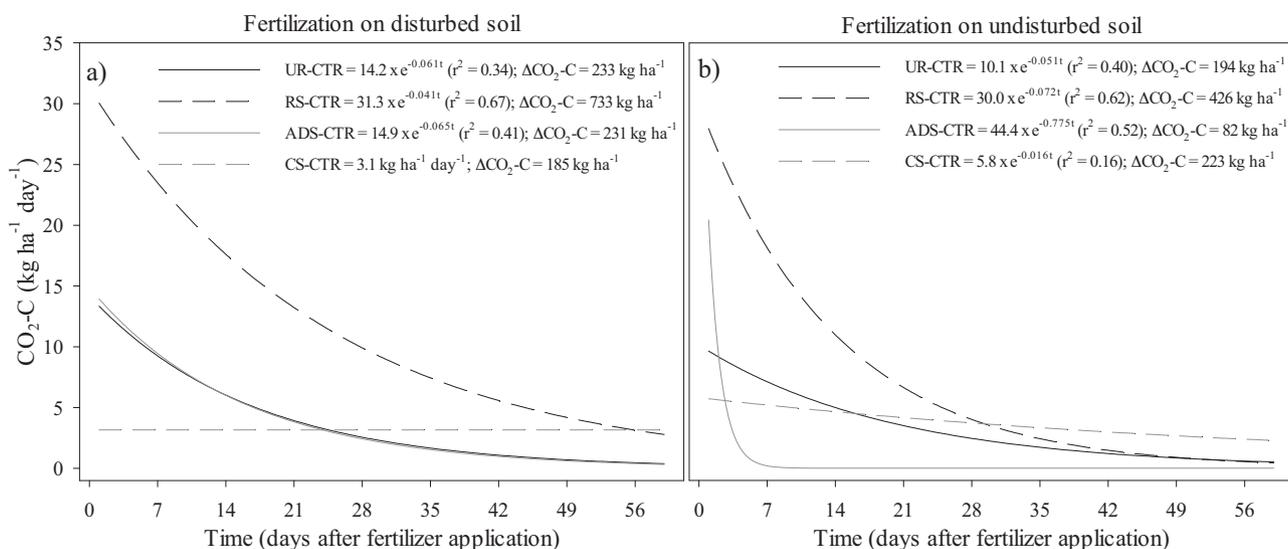


Fig. 3. Differential soil CO₂-C emission induced by fertilization treatments from disturbed (a) and undisturbed soil (b) according to a first-order exponential decay model ($(\Delta f(t) = C_0 k \times e^{-kt})$). Individual data points were omitted for simplicity. CTR: control without fertilization; UR: urea; RS: raw swine slurry; ADS: anaerobically digested swine slurry; CS: composted swine slurry.

79.7, 48.2, and 6.9% of the organic fertilizer-added C as RS, ADS, and CS, respectively, was mineralized and lost as CO₂. Thus, considering the balance between C inputs and measured short-term CO₂-C emissions, net C budgets of -233, 186, 249, and 2489 kg C ha⁻¹ were estimated in the DS+UR, DS+RS, DS+ADS, and DS+CS treatments in relation to DS+CTR, respectively. Although a higher potential for soil organic C accumulation was indeed expected for CS due to the higher amount of C added to the soil in this treatment (C input was 2.9 and 5.6 times higher in relation to RS and ADS, respectively), the quality of the CS-added C and the very low decomposition of this organic fertilizer (11.5 and 7 times lower than RS and ADS, respectively) had a stronger impact on the estimated net C budget than would be predicted only by C input quantity. In contrast, higher C input by RS did not result in a higher net C budget in relation to ADS. The lower decomposition of ADS resulted in a net C budget of 63 kg ha⁻¹ in relation to the RS amended soil.

The differential CO₂-C emission dynamics from the US+UR treatment was similar to that observed on for the DS+UR with an estimated C decay rate of 0.051 ± 0.012 day⁻¹ and a half-life of 13.6 days (Fig. 3b). The US+RS treatment had soil CO₂-C emissions starting at the level observed in the DS+RS yet with a higher C decay rate (0.072 ± 0.011 day⁻¹) and a shorter half-life (9.6 days). In contrast to the DS+ADS treatment, differential soil CO₂-C emissions decreased sharply for US+ADS (k = 0.775 ± 0.209 day⁻¹) and were very short-lived (t_{1/2} = 0.9 days). Nonetheless, the first-order decay model adjusted to US+CS estimated a C decay rate of 0.016 ± 0.006 day⁻¹ and a half-life of 43.3 days for that treatment.

The patterns regarding differential CO₂-C emissions from US amended with organic fertilizers were different from the DS treatment (Fig. 3a-b). The higher C decay rates of US+RS and US+ADS in comparison with the same treatments applied to the DS could be related to leaching of mineral N from the zone of active decomposition of crop residues at the soil surface in the US treatments (Giacomini and Aita, 2008). The first precipitation event (10 mm) occurred only 2 days after fertilizer application (Fig. 2) which coincided with a sharp decrease in soil CO₂-C emission from the US+ADS treatment (Fig. 3b). Thus, the soluble NH₄⁺-N added to soil by the RS and ADS could have been removed from the soil surface thereby avoiding direct contact with crop residues and decreasing their decomposition rates in US

treatments (Aita et al., 2012). This effect was more evident in US+ADS than US+RS due to the lower contribution of the recalcitrant ADS-added C for the soil CO₂-C emissions (Marcato et al., 2009).

The cumulative soil CO₂-C emissions from UR, RS, ADS, and CS treatments were 194, 426, 82, and 223 kg CO₂-C ha⁻¹ higher than CTR treatment under US, respectively (Fig. 3b). When the UR treatment was used as reference, soil CO₂-C emissions promoted by organic fertilizers were only 232 and 29 kg CO₂-C ha⁻¹ higher in RS and CS treatments, respectively, but 12 kg CO₂-C ha⁻¹ lower in ADS. Carbon mineralization of RS and ADS were lower under US than DS, representing 46.4 and 17.1% of the organic fertilizer-added C within these treatments. However, the mineralization of CS was not affected by soil disturbance level (8.3% under US). These results indicate a net C budget of -194, 493, 397, and 2452 kg C ha⁻¹ for US+UR, US+RS, US+ADS, and US+CS treatments in relation to US+CTR, respectively. The faster mineralization of RS-added C (46.4 and 79.7% for US and DS, respectively) in relation to other organic fertilizers (ADS and CS) corroborates previous results reporting no significant soil organic C accumulation in RS amended soils even when managed under no-till (Comin et al., 2013).

The recalcitrant nature of CS explains the low and similar mineralization of the CS-added C among DS and US treatments (6.9 and 8.3%, respectively). Although the DS+CS treatment received a greater C input than the DS+UR (173%; considering both fertilizer and crop residue-added C), soil CO₂ emissions decreased 20.5%. These results suggest that the low mineral N input through CS (12 kg NH₄⁺-N+NO₃⁻-N ha⁻¹) was rapidly immobilized in the soil (data not shown), impairing the decomposition of crop residues in relation to the UR treatments regardless of soil disturbance levels. These results confirm the CS potential for substantial soil organic C accumulation as reported for other organic fertilizers (Gulde et al., 2008; Nicoloso, 2009; Powlson et al., 2012). Additionally, previous swine slurry treatment by anaerobic digestion (ADS) or composting (CS) could also offset the increased CO₂-C emissions from RS amended soils (Yang et al., 2002; Marcato et al., 2009).

The conclusions about the potential of organic fertilizers to promote soil C sequestration should be viewed as preliminary due to the relatively short duration of this study and should not be extrapolated to long-term predictions. However, our study

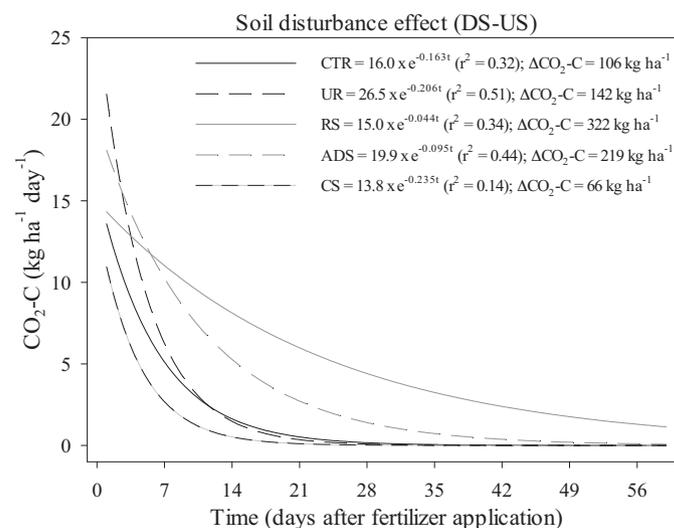


Fig. 4. Differential soil CO₂-C emission induced by soil disturbance from fertilization treatments according to a first-order exponential decay model ((Δf(t) = C₀k × e^{-kt}). Individual data points were omitted for simplicity. DS: disturbed soil; US: undisturbed soil; CTR: control without fertilization; UR: urea; RS: raw swine slurry; ADS: anaerobically digested swine slurry; CS: composted swine slurry.

provides relevant theoretical information regarding organic fertilizer decomposition and short-term CO₂ emissions from contrasting soil management systems which compliment long-term studies reporting soil organic C stocks changes due to organic amendments (Gulde et al., 2008; Lal, 2009; Nicoloso, 2009; Powlson et al., 2012). Additionally, our results would support other research addressing N losses and soil availability (Chantigny et al., 2002; Yang et al., 2002; Aita et al., 2012; Chalhoub et al., 2013) and the parametrization of mathematical models (e.g., CENTURY, RothC, DAISY, PASTIS) assessing changes on soil organic C stocks according to soil management and fertilization practices (Bruun et al., 2003; Yokozawa et al., 2010; Chalhoub et al., 2013; Cong et al., 2014). Future long-term studies assessing changes in soil organic C stocks due to soil tillage practices and organic fertilization should also address concomitant ammonia and greenhouse gases emissions (i.e., CH₄ and N₂O) from these practices (Aita et al., 2014b) to fully evaluate the environmental benefit of recycling such wastes in agricultural systems.

3.3. CO₂-C emission induced by soil disturbance

Total C input through wheat straw and organic fertilizer amendments was 1.54, 1.54, 2.46, 2.03, and 4.22 Mg C ha⁻¹ for CTR, UR, RS, ADS, and CS treatments, respectively (Table 1). Incorporation of crop residues into the soil promoted an increase in the cumulative differential soil CO₂-C efflux ranging from 66 to 322 kg CO₂-C ha⁻¹ when compared with US treatments (Fig. 4). These results represent 6.9, 9.2, 13.1, 10.8, and 1.6% of the total C input for CTR, UR, RS, ADS, and CS treatments, respectively.

The estimated C decay rate of the differential CO₂-C emissions between DS+CTR and US+CTR treatments was 0.163 ± 0.061 day⁻¹ ($p < 0.0001$) with a C half-life of 4.2 days, indicating a transient effect of soil disturbance on soil CO₂-C emissions. Previous studies reported lower and momentary peaks of short-term soil CO₂-C emissions induced by soil tillage in Ferralsols more than in other soil orders (Reicosky and Lindstrom, 1993; Reicosky et al., 1997; Pes et al., 2011), but no long-term emission difference between conventional tilled and no-tilled systems (Franzluebbers et al., 1995; Vargas and Scholles, 2000; Costa et al., 2008). Up to 80% of the increased CO₂-C emissions of conventional tilled Ferralsols are derived from the decomposition of crop residues incorporated into the upper soil layer (Pes et al., 2011). Although a faster decomposition of crop residues would be expected under conventional tillage (Campos et al., 2011), the strong organo-mineral interaction between the progressively decomposed crop residues and soil clay particles (Grandière et al., 2007) also would have impaired crop residue mineralization; this may explain the small difference between DS+CTR and US+CTR treatments on soil CO₂-C emissions.

The dynamics of differential soil CO₂-C emission between contrasting soil disturbance treatments (DS-US) was similar to those observed in the CTR treatment when the soil was amended with UR or CS, with estimated C decay rates of 0.206 ± 0.050 and 0.235 ± 0.153 day⁻¹ ($p < 0.01$ and $p = 0.13$, respectively) and C half-lives of 3.3 and 2.9 days, respectively. Nonetheless, RS and ADS amendments decreased C decay rates (0.044 ± 0.011 and 0.095 ± 0.022 day⁻¹, respectively) and increased C half-lives (15.7 and 7.3 days, respectively) when comparing contrasting soil disturbance treatments.

Differential soil CO₂-C emissions between contrasting soil disturbance treatments (DS-US) increased when the soil was amended with UR, RS, and ADS in relation to CTR. Extra labile C input from raw swine slurry supported a longer period of increased soil CO₂-C emissions from DS in relation to US. By contrast, CS amendment decreased the differential soil CO₂-C efflux (66 kg CO₂-C ha⁻¹) compared with the other treatments (106–322 kg CO₂-

Cha⁻¹). Soil disturbance in combination with high inputs of mineral N and labile C through organic fertilizers (such the RS) enhances soil CO₂-C emission and could ultimately decrease soil organic C stocks. However, application of humified organic residues with higher C/N ratio and low mineral N content such as the CS (Table 1) can impair crop residue decomposition and soil CO₂-C emission (Muhammad et al., 2011). Composted swine slurry amendment can even improve aggregation and fresh organic matter stabilization in soils under conventional tillage (Nicoloso, 2009). Thus, CS amendment could partially offset increased soil CO₂-C emissions promoted by intensive soil disturbance.

4. Conclusions

Short-term CO₂-C emissions from a Rhodic Nitisol were increased by intensive soil disturbance. High mineral N inputs through mineral or organic fertilizers enhance the decomposition of crop residues and the soil CO₂-C efflux. Extra labile C input through RS amendment sustained longer increased soil CO₂-C emissions, resulting in higher CO₂-C losses than observed with other fertilizers. Nonetheless, recalcitrant C input from ADS and CS had limited direct contribution to CO₂-C emissions from both disturbed and undisturbed soils. The high positive net C budget with CS amendment presents a genuine potential for substantial soil organic C accumulation over mineral fertilization while offsetting increased CO₂-C emissions in comparison to RS amended soils.

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References

- Aita, C., Chiapinotto, I.C., Giacomini, S.J., Hübner, A.P., Marques, M.G., 2008. Decomposition of black oat straw and pig slurry in a soil under no-tillage. *R. Bras. Ci. Solo* 30, 149–161 (in Portuguese).
- Aita, C., Recous, S., Cargnin, R.H.O., Luz, L.P., Giacomini, S.J., 2012. Impact on C and N dynamics of simultaneous application of pig slurry and wheat straw, as affected by their initial locations in soil. *Biol. Fertil. Soils* 48, 633–642.
- Aita, C., Giacomini, S.J., Pujol, S.B., Nicoloso, R.S., Corrêa, J.C., 2014a. Swine and cattle manure use as fertilizer: environmental impacts and mitigation strategies. In: Palhares, J.C.P., Gebler, L. (Eds.), *Gestão Ambiental na Agropecuária*, vol. 2. Embrapa, Brasília, pp. 199–234 (in Portuguese).
- Aita, C., Gonzatto, R., Miola, E.C.C., Santos, D.B., Rochette, P., Angers, D.A., Chantigny, M.H., Pujol, S.B., Giacomini, D.A., Giacomini, S.J., 2014b. Injection of dicyandiamide-treated pig slurry reduced ammonia volatilization without enhancing soil nitrous oxide emissions from no-till corn in southern Brazil. *J. Environ. Qual.* 43, 789–800.
- Angnes, G., Nicoloso, R.S., Da Silva, M.L.B., Oliveira, P.A.V., Higarashi, M.M., Mezzari, M.P., Miller, P.R.M., 2013. Correlating denitrifying catabolic genes with N₂O and N₂ emissions from swine slurry composting. *Biores. Technol.* 140, 368–375.
- Bertora, C., Alluvione, F., Zavattaro, L., Van Groenigen, J.W., Velthof, G., Grignani, C., 2008. Pig slurry treatment modifies slurry composition N₂O, and CO₂ emissions after soil incorporation. *Soil Biol. Biochem.* 40, 1999–2006.
- Bruun, S., Christensen, B.T., Hansen, E.M., Magid, J., Jensen, L.S., 2003. Calibration and validation of the soil organic matter dynamics of the Daisy model with data from the Askov long-term experiments. *Soil Biol. Biochem.* 35, 67–76.
- Carrington, E.M., Hernes, P.J., Dyda, R.Y., Plante, A.F., Six, J., 2012. Biochemical changes across a carbon saturation gradient: lignin, cutin and suberin decomposition and stabilization in fractionated carbon pools. *Soil Biol. Biochem.* 47, 179–190.
- Chalhoub, M., Garnier, P., Coquet, Y., Mary, B., Lafolie, F., Houot, S., 2013. Increased nitrogen availability in soil after repeated compost applications: Use of the PASTIS model to separate short and long-term effects. *Soil Biol. Biochem.* 65, 144–157.
- Chantigny, M.H., Rochette, P., Angers, D.A., 2001. Short-term C and N dynamics in a soil amended with pig slurry and barley straw: a field experiment. *Can. J. Soil Sci.* 81, 131–137.
- Chantigny, M.H., Angers, D.A., Rochette, P., 2002. Fate of carbon and nitrogen from animal manure and crop residues in wet and cold soils. *Soil Biol. Biochem.* 34, 509–517.

- Chatskikh, D., Olesen, J.E., 2007. Soil tillage enhanced CO₂ and N₂O emissions from loamy sand soil under spring barley. *Soil Till. Res.* 97, 5–18.
- Chaves, L.F., Amado, T.J.C., Bayer, C., La Scala, N.J., Escobar, L.F., Fiorin, J.E., Campos, B.-H.C., 2009. Carbon dioxide efflux in a Rhodic Hapludox as affected by tillage systems in southern Brazil. *Rev. Bras. Ci. Solo* 33, 325–334.
- Comin, J.J., Loss, A., Veiga, M., Guardini, R., Schmitt, D.E., Oliveira, P.A.V., Belli Filho, P., Couto, R.R., Benedet, L., Müller Junior, V., Brunetto, G., 2013. Physical properties and organic carbon content of a Typic Hapludult soil fertilised with pig slurry and pig litter in a no-tillage system. *Soil Res.* 51, 459–470.
- Cong, R., Wang, X., Xu, M., Ogle, S.M., Parton, W.J., 2014. Evaluation of the CENTURY model using long-term fertilization trials under corn–wheat cropping systems in the typical croplands of China. *PLoS One* 9, e95142.
- Costa, F.S., Bayer, C., Zanatta, J.A., Mielniczuk, J., 2008. Carbon stock and carbon dioxide emissions as affected by soil management systems in Southern Brazil. *R. Bras. Ci. Solo* 32, 323–332 (in Portuguese).
- Comissão de Química e Fertilidade do Solo – RS/SC (CQFS RS/SC), 2004. Liming and fertilizing manual for Rio Grande do Sul and Santa Catarina States (10th ed.). Sociedade Brasileira de Ciência do Solo–Núcleo Regional Sul Porto Alegre, RS, p. 400 (In portuguese).
- Drewitt, G., Wagner-Riddle, C., Warland, J., 2009. Isotopic CO₂ measurements of soil respiration over conventional and no-till plots in fall and spring. *Agric. Forest Meteorol.* 149, 614–622.
- EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA. 2004. Centro Nacional de Pesquisa de Solos. Solos do Estado de Santa Catarina. Rio de Janeiro, (Boletim de Pesquisa e Desenvolvimento, 46) (in portuguese), 726p.
- FAO, 1998. World Reference Base for Soil Resources. FAO, Rome, Italy.
- Franzluebbers, A.J., Hons, F.M., Zuberer, D.A., 1995. Tillage-induced seasonal changes in soil physical properties affecting soil CO₂ evolution under intensive cropping. *Soil Till. Res.* 34, 41–60.
- Giacomini, S.J., Aita, C., 2008. Carbon dioxide emission after application of pig slurry and pig deep-litter. *Pesq. Agropec. Bras.* 43, 107–114 (in Portuguese).
- Grandière, I., Razafimbelo, T., Barthès, B., Blanchart, E., Louri, J., Ferrer, H., Chenu, C., Wolf, N., Albrecht, A., Feller, C., 2007. Effet de différents systèmes en semis direct avec couverture végétale (SCV) sur la distribution granulo-densimétrique de la matière organique d'un sol argileux des Hautes Terres de Madagascar. *Etude et Gestion des Sols* 14, 117–133.
- Guide, S., Chung, H., Amelung, W., Chang, C., Six, J., 2008. Soil carbon saturation controls labile and stable carbon pool dynamics. *Soil Sci. Soc. Am. J.* 72, 605–612.
- Kirchmann, H., Lundvall, A., 1993. Relationships between N immobilization and volatile fatty acids in soil after application of pig and cattle slurry. *Biol. Fertil. Soils* 15, 161–164.
- Kunz, A., Hiagarashi, M.M., Oliveira, P.A.V., 2005. Technologies for management and treatment of hog manure assessed by research institutions in Brazil. *Cad. Ciên. Tecnol.* 22, 651–665 (in Portuguese).
- Kunz, A.L., Miele, M., Steinmetz, R.L.R., 2009. Advanced swine manure treatment and utilization in Brazil. *Biores. Technol.* 100, 5485–5489.
- Lal, R., 2009. Challenges and opportunities in soil organic matter research. *Eur. J. Soil Sci.* 60, 158–169.
- La Scala Jr., N., Bolonhezi, D., Pereira, G.T., 2006. Short-term soil CO₂ emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. *Soil Till. Res.* 91, 244–248.
- La Scala Jr., N., Lopes, A., Spokas, K., Bolonhezi, D., Archer, D.W., Reicosky, D.C., 2008. Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model. *Soil Till. Res.* 99, 108–118.
- Lanzanova, M.E., Eltz, F.L.F., Nicoloso, R.S., Amado, T.J.C., Reinert, D.J., Rocha, M.R., 2010. Physical properties of a typic paleudalf under long-term no-tillage and cropping systems. *R. Bras. Ci. Solo* 34, 1333–1342 (in Portuguese).
- Linn, D.M., Doran, J.W., 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. *Soil Sci. Soc. Am. J.* 48, 1267–1272.
- Marcato, C.E., Mohtar, R., Revel, J.C., Pouech, P., Hafidi, M., Guiesse, M., 2009. Impact of anaerobic digestion on organic matter quality in pig slurry. *Int. Biodegr. Biodegr.* 63, 260–266.
- Muhammad, W., Vaughan, S.M., Dalal, R.C., Menzies, N.W., 2011. Crop residues and fertilizer nitrogen influence residue decomposition and nitrous oxide emission from a Vertisol. *Biol. Fertil. Soils* 47, 15–23.
- Nicoloso, R.S., 2009. Soil organic carbon stocks and stabilization mechanisms on temperate and subtropical climate agroecosystems. PhD. Thesis. Federal University of Santa Maria, pp. 125.
- Nicoloso, R.S., Bayer, C., Denega, G.L., Oliveira, P.A.V., Higarashi, M.M., Correa, J.C., Lopes, L.S., 2013. Gas chromatography and photoacoustic spectroscopy for the assessment of soil greenhouse gases emissions. *Ci. Rural* 43, 262–269.
- Pes, L.Z., Amado, T.J.C., La Scala Jr., N., Bayer, Fiorin, C., 2011. The primary sources of carbon loss during the crop-establishment period in a subtropical Oxisol under contrasting tillage systems. *Soil Till. Res.* 117, 163–171.
- Powelson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K. W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. *Agric. Ecosyst. Environ.* 146, 23–33.
- Razafimbelo, T.M., Albrecht, A., Oliver, R., Chevallier, T., Chapuis-Lardy, L., Feller, C., 2008. Aggregate associated-C and physical protection in a tropical clayey soil under Malagasy conventional and no-tillage systems. *Soil Till. Res.* 98, 140–149.
- Reicosky, D.C., 1997. Tillage-induced CO₂ emission from soil. *Nutr. Cycl. Agroecosyst.* 49, 273–285.
- Reicosky, D.C., Lindstrom, N.J., 1993. Fall tillage method: effect on short-term carbon dioxide flux from soil. *Agron. J.* 85, 1237–1245.
- Reicosky, D.C., Dugas, W.A., Torbert, H.A., 1997. Tillage-induced soil carbon dioxide loss from different cropping systems. *Soil Till. Res.* 41, 105–118.
- Rochette, P., Angers, D.A., Chantigny, M.H., MacDonald, J.D., Gasser, M.-O., Bertrand, N., 2009. Reducing ammonia volatilization in a no-till soil by incorporating urea and pig slurry in shallow bands. *Nutr. Cycl. Agroecosyst.* 84, 71–80.
- USDA-FAS, 2014. Livestock and Poultry: Word Markets and Trade. USDA-FAS, April 2014. (http://apps.fas.usda.gov/psdonline/circulars/livestock_poultry.pdf) (accessed 05.05.14.).
- Vargas, L.K., Scholles, D., 2000. Microbial biomass and C-CO₂ and mineral nitrogen production in Paleudult soil cultivated under different management systems. *R. Bras. Ci. Solo* 24, 35–42 (in Portuguese).
- Vivan, M., Kunz, A., Stolber, J., Perdomo, C., Techio, V.H., 2010. Efficiency of biodigester and stabilization pond interaction in removal of swine manure pollutants. *Rev. Bras. Eng. Agric. Ambient.* 14, 320–325 (in Portuguese).
- Yamulki, S., Jarvis, S.C., 1999. Automated chamber technique for gaseous flux measurements: evaluation of a photoacoustic infrared spectrometer-trace gas analyzer. *J. Geophys. Res.* 104, 5463–5469.
- Yang, X.M., Drury, C.F., Reynolds, W.D., McKenney, D.J., Tan, C.S., Zhang, T.Q., Fleming, R.J., 2002. Influence of composts and liquid pig manure on CO₂ and N₂O emissions from a clay loam soil. *Can. J. Soil Sci.* 82, 395–401.
- Yokozawa, M., Shirato, Y., Sakamoto, T., Yonemura, S., Nakai, M., Ohkura, T., 2010. Use of the RothC model to estimate the carbon sequestration potential of organic matter application in Japanese arable soils. *Soil Sci. Plant Nutr.* 56, 168–176.
- Zhong, J., Wei, Y., Wan, H., Wu, Y., Zheng, J., Han, S., Zheng, B., 2013. Greenhouse gas emission from the total process of swine manure composting and land application of compost. *Atmos. Environ.* 81, 348–355.