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Short-term temporal changes of soil carbon losses after tillage described by a first-order decay model

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Abstract

Tillage stimulates soil carbon (C) losses by increasing aeration, changing temperature and moisture conditions, and thus favoring microbial decomposition. In addition, soil aggregate disruption by tillage exposes once protected organic matter to decomposition. We propose a model to explain carbon dioxide (CO_2) emission after tillage as a function of the no-till emission plus a correction due to the tillage disturbance. The model assumes that C in the readily decomposable organic matter follows a first-order reaction kinetics equation as: $dC_{sail}(t)/dt = -kC_{soil}(t)$ and that soil C-CO_2 emission is proportional to the C decay rate in soil, where $C_{soil}(t)$ is the available labile soil C (g m^{-2}) at any time (t). Emissions are modeled in terms soil C available to decomposition in the tilled and non-tilled plots, and a relationship is derived between no-till (F_{NT}) and tilled (F_T) fluxes, which is: $F_T = a_1 F_{NT}\,e^{-a_2 t}$, where t is time after tillage. Predicted and observed fluxes showed good agreement based on determination coefficient (R^2), index of agreement and model efficiency, with R^2 as high as 0.97. The two parameters included in the model are related to the difference between the decay constant (k factor) of tilled and no-till plots (a_2) and also to the amount of labile carbon added to the readily decomposable soil organic matter due to tillage (a_1). These two parameters were estimated in the model ranging from 1.27 and 2.60 (a_1) and -1.52×10^{-2} and 2.2×10^{-2} day^{-1} (a_2). The advantage is that temporal variability of tillage-induced emissions can be described by only one analytical function that includes the no-till emission plus an exponential term modulated by tillage and environmentally dependent parameters.

Keywords: Soil respiration; Soil tillage; No-till; Soil organic matter; Labile carbon decay; CO_2 flux

1. Introduction

Land use changes that have contributed most to the atmospheric CO_2 increase are caused by increased soil respiration. Agricultural related activities such as deforestation, soil tillage, liming and irrigation are the main causes of a decrease in soil C associated with an increase in decomposition (Schlesinger, 1999; Read et al., 2001; Lal et al., 1995). Mann (1986) analyzed global losses of soil C following cultivation of forest or grasslands indicating a reduction of 20% of the initial soil organic C (1500 g m^{-2} in the top 30 cm of soil) mainly in the first 5 years after conversion. Further work has also shown that a change from conventional tillage to non-tillage could help sequester as much as 57 ± 14 g C m^{-2} year^{-1}, 5–10 years after conversion

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(West and Post, 2002). Recent studies have shown even higher no till soil C stock potential: 94% and 76% more light and heavy C fraction accumulation in the first 20 cm depth, respectively, when compared to conventional tillage practices (Tan et al., 2004).

Tillage-induced soil C loss has been shown to be important especially in the short-term periods. Similar to deforestation and biomass burning, soil tillage accelerates organic C oxidation releasing high amounts of CO_2 to the atmosphere in a few weeks (La Scala et al., 2006, 2001; Prior et al., 2000; Ellert and Janzen, 1999; Rochette and Angers, 1999; Reicosky et al., 1997; Reicosky and Lindstrom, 1993). One factor related to tillage that contributes to soil C losses is soil aggregate disruption and transfer of labile or fresh organic matter once protected by aggregates to unprotected readily decomposable organic matter (Grandy and Robertson, 2007; De Gryze et al., 2006; Six et al., 1999). Jacinthe and Lal (2005) have shown that protected C accounted for about 0.5% of the total organic carbon in the surface layer 0–5 cm of soils in no-till cropland. Tillage also reduces bulk density thereby increasing total porosity, promoting gas diffusion and convection with improved oxygen, temperature and moisture for decomposition (Sartori et al., 2006; Molina et al., 1983). The tillage-induced CO_2 emission is mostly related to light fraction (LF) organic matter decay, or labile carbon decay, that has a more rapid turnover time than total soil C (Wander et al., 1994; Swanston et al., 2002; De Gryze et al., 2004). In recent work, Grandy and Robertson (2006) have shown that the proportion of intra-aggregate LF to total LF in macroaggregates declined from 28% to 16% within 60 days after cultivation. Tillage disrupts the aggregates exposing once protected fresh organic matter (Wright and Hons, 2005; Jacinthe and Lal, 2005; Bronick and Lal, 2005) that coupled with increases in soil temperature and other environmental changes, accelerates soil organic matter (SOM) decomposition (Grandy et al., 2006). Certainly, quantifying the increase in soil CO_2 flux shortly after tillage will help our understanding of tillage-induced releases of protected soil C and changes in SOM decomposition rates.

In bare soils measurement of CO_2 exchange is also a measure of the rate of SOM decomposition as a result of microbial respiration, since no root activity exists. La Scala et al. (2001, 2005, 2006) evaluated soil CO_2 flux after different tillage methods relative to the flux from a no till treatment (NT) and found similar temporal trends in the CO_2 flux for 3–4 weeks after several tillage methods. In such experiments, similarity in the temporal trends among the NT and tillage treatments, presumably in response to temperature and water content changes, suggests that the NT emission could be used as a baseline to enable predictions of CO_2 emissions after tillage. Observations where emission fluctuations (increases and decreases) after tillage are mimicked in the no-till curves have been reported by several authors (La Scala et al., 2001, 2005, 2006; Reicosky, 2002; Rochette and Angers, 1999; Fortin et al., 1996; Prior et al., 1997; Franzluebbers et al., 1995). The soil C-CO_2 flux in tilled plots can be described as result of a natural plus a tillage-induced emission. Emissions from tilled treatments are addressed in terms of the non-disturbed emission plus a tillage induced component assuming labile C in SOM decays following a first order differential equation. The advantage of this method is that the temporal variability of tillage-induced emissions can be described by a single analytical function that includes the no-till emission plus an exponential term in time modulated by tillage and environmentally dependent parameters.

The objective of this paper is to present a simple method based on the non-disturbed emissions that could be used for predictions of soil C losses after tillage.

1.1. The proposed model

A schematic representation of the physical aspects included in our model is described in Fig. 1. First, we consider that the amount of labile C in unprotected and readily decomposed SOM in tilled (T) plot ($C_{NT} + C_T$) is higher than the one in the no-till (NT) plot (C_{NT}) because of the additional amount introduced due to aggregate disruption after tillage (C_T). Also the soil layer in the tilled plot is assumed to be less dense and with a soil structure that is favorable to gas diffusion and convection. Initially, both fluxes in the NT and T plots are proportional to the rate of labile carbon decay in the unprotected SOM: $F_{NT} \alpha \mathrm{d}C_{NT}/\mathrm{d}t$ and $F_T \alpha \mathrm{d}C_{NT}/\mathrm{d}t + \mathrm{d}C_T/\mathrm{d}t$, respectively. We prefer addressing fluxes in terms of C-CO_2 fluxes, instead of CO_2, as these would be directly related to the C decay units in soil. The model assumes that soil C decay follows a first-order reaction kinetics equation as:

$$\frac{\mathrm{d}C_{\mathrm{soil}}(t)}{\mathrm{d}t} = -kC_{\mathrm{soil}}(t) \tag{1}$$

where C_{soil} is the amount of labile C of readily decomposable organic matter (g m^{-2}), k the decay constant or decay factor (time^{-1}) and t is the time after tillage. Solving the above equation, we obtain:

$$C_{\mathrm{soil}}(t) = C_0\,\mathrm{e}^{-kt} \tag{2}$$

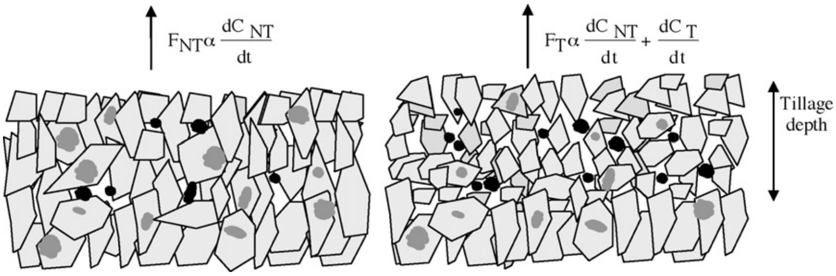

Fig. 1. Schematic representation of free (black) and aggregate protected (grey) labile C in the no-till (left) and tilled (right) plots after tillage. Tillage releases C from aggregates resulting in an increase of labile C available for microbial decay.

where $C_{\mathrm{soil}}(t)$ is the available labile soil C (g m^{-2}) for decomposition at any time t. It is important to notice that the so called decay constant (k, time^{-1}) will be assumed here as constant justified by the short-term nature of the field experiment (1 month). Typically, the decay constant (k) is described in literature as an exponential and logarithm dependent on soil temperature and soil moisture, respectively (Parton et al., 1994). Eq. (2) shows that with no additional soil C input, the initial amount of the available labile C in soil (C_0) should decay exponentially in time controlled by the decay constant (k).

Soil CO_2 emission, primarily from microbial respiration, can be described by Eq. (2), especially in bare soils. Not all C from organic matter decomposition is transferred immediately to CO_2, part of the C can be incorporated into microbial biomass, depending on microbial efficiency (Stevenson and Cole, 1999). A reasonable assumption is that C-CO_2 (F) emission is proportional to the decay rate with a negative sign. The higher the decay rate the higher the soil C-CO_2 emission:

$$F(t)\alpha - \frac{\mathrm{d}C_{\mathrm{soil}}(t)}{\mathrm{d}t} \tag{3}$$

Substituting Eq. (3) in Eq. (2) above yields:

$$F(t)\alpha - \frac{\mathrm{d}C_{\mathrm{soil}}(t)}{\mathrm{d}t} = -\frac{\mathrm{d}}{\mathrm{d}t}(C_0\,\mathrm{e}^{-kt})$$

$$F(t)\alpha C_0 k\,\mathrm{e}^{-kt}$$

The relationship above is presented as proportionality but we will assume this as equality because microbial biomass contributes to the decaying process after microbes death. The decay factor (k) estimated here will not be a decay of only one soil C component, but will include C in microbial biomass emitted in later respiration. In any case C that is kept in soil, even in the form of microbial biomass, will eventually decay in time (Eq. (1)).

$$F(t) = C_0 k\,\mathrm{e}^{-kt} \tag{4}$$

The effect of tillage on soil CO_2 flux is described by taking into account: (a) the additional tillage-induced C amount to the decay process and (b) a change in the decay factor k due to changes in soil physical properties caused by tillage. Let us assume that immediately after tillage ($t = 0$), the tillage-induced C contributing to the decay process $C_{0\mathrm{T}}$ (T, from tillage type) is then added to the labile C that existed there before tillage $C_{0\mathrm{NT}}$ (NT, from non-tillage):

$$C_{\mathrm{T}}(t = 0) = C_{0\mathrm{NT}} + C_{0\mathrm{T}}$$

where $C_{\mathrm{T}}(t = 0)$ is the total unprotected labile C just after tillage that is equal to the unprotected labile C available before tillage (the same as for a NT plot) plus the tillage-induced component due to aggregate disruption ($C_{0\mathrm{T}}$). So, at any time (t) after tillage, the amount of labile C in tilled plot follows below:

$$C_{\mathrm{Soil}}(t) = C_{\mathrm{NT}}(t) + C_{\mathrm{T}}(t) \tag{5}$$

As supposed for the tillage plot, C-CO_2 emission comes from soil labile organic matter oxidation given by:

$$F_{\mathrm{T}} = -\frac{\mathrm{d}C_{\mathrm{Soil}}}{\mathrm{d}t} = -\frac{\mathrm{d}}{\mathrm{d}t}(C_{\mathrm{NT}} + C_{\mathrm{T}}) = -\frac{\mathrm{d}C_{\mathrm{NT}}}{\mathrm{d}t} - \frac{\mathrm{d}C_{\mathrm{T}}}{\mathrm{d}t} \tag{6}$$

Therefore, the soil C-CO_2 flux would be given by:

$$F_{\mathrm{T}}(t) = C_{0\mathrm{NT}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t} + C_{0\mathrm{T}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t}$$

Multiplying the above equation by the no-till C-CO_2 flux, we have:

$$F_{\mathrm{T}}(t) = [C_{0\mathrm{NT}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t} + C_{0\mathrm{T}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t}]\frac{C_{0\mathrm{NT}}k_{\mathrm{NT}}\,\mathrm{e}^{-k_{\mathrm{NT}}t}}{C_{0\mathrm{NT}}k_{\mathrm{NT}}\,\mathrm{e}^{-k_{\mathrm{NT}}t}}$$

$$F_{\mathrm{T}}(t) = [C_{0\mathrm{NT}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t} + C_{0\mathrm{T}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t}]\frac{F_{\mathrm{NT}}}{C_{0\mathrm{NT}}k_{\mathrm{NT}}\,\mathrm{e}^{-k_{\mathrm{NT}}t}}$$

$$F_{\mathrm{T}}(t) = \left[\frac{C_{0\mathrm{NT}}k_{\mathrm{T}}\,\mathrm{e}^{-k_{\mathrm{T}}t} + C_{0\mathrm{T}}k_{T}\,\mathrm{e}^{-k_{\mathrm{T}}t}}{C_{0\mathrm{NT}}k_{\mathrm{NT}}\,\mathrm{e}^{-k_{\mathrm{NT}}t}}\right]F_{\mathrm{NT}}(t) \tag{7}$$

At this point, we assumed that the k_T and k_{NT} factors are different from each other, but defining $k_T = b_T k_{NT}$ the decay constant after tillage is proportional to the decay constant in the non-tillage plot by a factor b_T, which is likely >1. It is important to notice that b_T will also depend on tillage applied (index T). If we substitute $k_T = b_T k_{NT}$ into the equation above we get:

$$F_T(t) = \left[\frac{C_{0NT} b_T k_{NT}\,e^{-b_T k_{NT} t} + C_{0T} b_T k_{NT}\,e^{-b_T k_{NT} t}}{C_{0NT} k_{NT}\,e^{-k_{NT} t}}\right] F_{NT}(t) \tag{8}$$

Cancelling the $k_{NT}(t)$ in the numerator and denominator of the equation above, and rearranging terms we get:

$$F_T(t) = b_T \left[\frac{C_{0NT} + C_{0T}}{C_{0NT}}\right] e^{-(b_T - 1)k_{NT} t} F_{NT}(t) \tag{9}$$

Eq. (9) describes the tillage-induced emission as a function of the non-tillage emission by multiplying it with an exponential term in time and also by a term that depends on how much of labile C was induced and non-induced by tillage immediately after tillage (C_{0NT} and C_{0T}). If we define $a_1 = b_T(C_{0NT} + C_{0T})/C_{0NT}$ and $a_2 = (b_T - 1)k_{NT} = k_T - k_{NT}$ we have:

$$F_T = a_1 F_{NT}\,e^{-a_2 t} \tag{10}$$

The expression above would describe the emissions after tillage as a function of the no-till emission and time, once a_1 and a_2 parameters are known for bare soils, where the sole C emission is from microbial activity alone. The physical meaning of a_1 and a_2 are given above and these are related to how much labile C was induced by tillage into the decay process (C_{0T}) and how the decay factor was altered by the tillage event. The a_2 factor is equal to the difference between the tilled to no-till plot decay factors, while a_1 is also dependent on the ratio between total labile C in the tilled plot related to the no-till one. The model seems realistic in the sense that the higher the NT emission, the higher the tillage-induced emissions. Eq. (10) was derived by assuming that soil C emission was only from soil C decay without root respiration.

2. Materials and methods

The theoretical model was applied to experimental data obtained from four experiments conducted in separate studies in the years of 1998, on a Barnes loam soil in Northern USA, and 2000, 2002 and 2003–2004 on a red latosol in southern Brazil. The Northern USA experiment was conducted at the Barnes-Aastad Association Swan Lake research farm in west central Minnesota, on a Barnes Loam (fine loamy mixed soil) with soil C content typically equal to 32 g kg^{-1}, having a crop history of wheat, soybeans and corn under conservation tillage. Experiments conducted in Southern Brazil in 2000 and 2002 were carried out at the experimental farm of the FCAV/UNESP campus, on a soil that is currently used for intensive experimental practices, cropping wheat, soybeans and sugarcane, and having a soil C content that is typically 11 g kg^{-1}. The third experiment (2003–2004) was conducted also in Southern Brazil, in APTA agency in the city of Ribeirão Preto, São Paulo State, in a soil that has 20 g kg^{-1} soil C content. That area has been cropped with sugarcane over the last 20 years using conservation tillage practices.

For all of these soils, CO_2 flux measurements were performed using an IRGA (infrared gas analyzer) produced by LiCor, NE, USA, either with a commercial LI-6400 system or a portable chamber system coupled to a four-wheel drive tractor designed for soil flux measurements. The data were extracted from previously published studies. The detailed experimental procedures used for CO_2 emission measurements in each study can be found in La Scala et al. (2001, 2005, 2006) and Reicosky (2002).

Each of the four experiments selected compared various tillage treatments to a no-till control (Table 1). Experiments I and II were conducted on bare fallow soil, where the area was mechanically harvested months before the tillage experiment. Experiment I tested the effect of four different tillage systems on CO_2 emissions, while experiment II used a single tillage implement (rotary tiller) with different adjustments for each of the four treatments. In experiments III and IV, planting had occurred and some vegetation had emerged by the end of the experiment. In experiment III, moldboard plow tillage was compared to chisel plow, and experiment IV had only the moldboard plow treatment.

Statistica software (StatSoft, Inc.) was used for fitting the experimental data to the model. Model parameters were estimated using non-linear least square estimation with the Gauss-Newton method. During the data fitting process, a_1 and a_2 values were initially set to zero, and the number of iterations before getting the final parameters values was never higher than 10.

Model performance was evaluated by comparing model predicted and observed values using linear regression, coefficient of determination (R^2), index of agreement (d-index) and modeling efficiency (ME). Index of agreement (d-index) was calculated with the

Table 1
Site and tillage description in each study where the model was applied

Experiment	Site description	Tillage treatment description	Tillage depth (cm)
I	Bare red latosol	RT: Rotary tiller, one pass with rotor rotation of 172 rpm raised rear shield	20
	22°15′S, 48°18′W	CP: Chisel plow, one pass, five shanks with 1.5 depth/spacing ratio	20
		DO: Reversible disk plow followed by offset disk harrow	20
		HO: Heavy offset disk harrow, one pass followed by offset disk harrow	20
		NT: No-till	
II	Bare red latosol	R122-U: Rotary tiller with a rotor rotation of 122 rpm. Raised rear shield	20
	22°15′S, 48°18′W	R153-U: Rotary tiller with rotor rotation of 153 rpm. Raised rear shield	20
		R153-D: Rotary tiller: with rotor rotation of 153 rpm. Rear shield lowered	20
		R216-D: Rotary tiller with rotor rotation of 216 rpm. Rear shield lowered	20
		NT: No-till	
III	Dark red latosol	MP: Moldboard plowing followed by two applications of offset disk harrow	30
	22°11′S, 47°48′W	CP: Chisel plow: one pass, five shanks with 1.5 depth/spacing ratio	30
		NT: No-till	
IV	Barnes loam	MP: Moldboard plowing	25
	45°41′N, 95°47′W	NT: No-till	

following expression:

$$d = 1 - \frac{\sum_{t=1}^{n}\left(F_t^{\text{obs}} - F_t^{\text{pred}}\right)^2}{\sum_{t=1}^{n}\left(\left|F_t^{\text{obs}} - \bar{F}^{\text{obs}}\right| + \left|F_t^{\text{pred}} - \bar{F}^{\text{obs}}\right|^2\right)}$$

where F_t^{obs} is the observed emission at an specific time after tillage t, with a mean emission throughout the experiment as $\bar{F}^{\text{obs}}$, and F_t^{pred} is the predicted emission at that time t (Willmott, 1981; Mayer and Butler, 1993; Legates and Mc Cabe, 1999). The value of d will vary between 0 and 1 with a value of 1 indicating perfect agreement (Willmott, 1981).

Model efficiency (ME), also known as one of the expressions of R^2 (coefficient of determination) in non-linear fitting evaluations, was calculated by the following formula:

$$\text{ME} = 1 - \frac{\sum_{t=1}^{n}\left(F_t^{\text{obs}} - F_t^{\text{pred}}\right)^2}{\sum_{t=1}^{n}\left(F_t^{\text{obs}} - \bar{F}^{\text{obs}}\right)^2}$$

where F_t^{obs}, $\bar{F}^{\text{obs}}$ and F_t^{pred} have the same meanings as described above (Mayer and Butler, 1993; Legates and Mc Cabe, 1999). Model efficiency will vary between minus infinity and 1 with higher values (closer to 1) indicative of superior performance. These two last indexes represent an improvement over R^2 only for model evaluation as these are sensitive to differences in the observed and model predicted means (Legates and Mc Cabe, 1999). Comparisons were performed for measured emission at each time after tillage versus result predicted from the model.

3. Results and discussions

Results of modeling soil C-CO_2 emission by fitting Eq. (10) to the data of experiments I and II are presented in Tables 2 and 3, respectively. The coefficient of determination (R^2), d-index and ME for all treatments show good agreement between observed and predicted values in both experiments. Experiment I data showed

Table 2
Estimated model parameters ± standard error, R^2, d-index, ME and total emissions (observed/predicted) of experiment I (Table 1)

Treatment	Model $F_T = a_1 F_{NT}\,e^{-a_2 t}$	R^2	d-index	ME	Total emission obs./Pred. (gC CO_2 m^{-2})
RT	$a_1 = 1.51 \pm 3.72 \times 10^{-2}$, $a_2 = 8.97 \times 10^{-3} \pm 2.29 \times 10^{-3}$	0.96	0.989	0.958	40.74/40.72
HO	$a_1 = 1.67 \pm 8.44 \times 10^{-2}$, $a_2 = -7.29 \times 10^{-3} \pm 4.78 \times 10^{-3}$[a]	0.88	0.962	0.875	43.49/44.21
DO	$a_1 = 1.95 \pm 7.09 \times 10^{-2}$, $a_2 = 1.37 \times 10^{-3} \pm 3.84 \times 10^{-3}$[a]	0.94	0.983	0.935	46.32/46.30
CP	$a_1 = 2.60 \pm 8.69 \times 10^{-2}$, $a_2 = 2.22 \times 10^{-2} \pm 4.52 \times 10^{-3}$	0.97	0.992	0.969	48.94/49.01

$[a_1]$ = Non-dimensional. $[a_2]$ = day^{-1}.
[a] Non-significant at $p > 0.01$.

Table 3
Estimated model parameters ± standard error, R^2, d-index, ME and total emissions (observed/predicted) of experiment II (Table 1)

Treatment	Model $F_T = a_1 F_{NT} e^{-a_2 t}$	R^2	d-index	ME	total emission obs./ pred (gC CO_2 m^{-2})
R122-U	$a_1 = 1.27 \pm 1.82 \times 10^{-2}$, $a_2 = 5.98 \times 10^{-3} \pm 1.14 \times 10^{-3}$	0.91	0.979	0.912	28.25/28.13
R153-U	$a_1 = 1.67 \pm 4.97 \times 10^{-2}$, $a_2 = 1.13 \times 10^{-2} \pm 2.50 \times 10^{-3}$	0.84	0.953	0.836	34.34/34.38
R153-D	$a_1 = 1.89 \pm 4.74 \times 10^{-2}$, $a_2 = 1.36 \times 10^{-2} \pm 2.15 \times 10^{-3}$	0.90	0.972	0.895	37.81/37.83
R216-D	$a_1 = 2.03 \pm 5.40 \times 10^{-2}$, $a_2 = 1.54 \times 10^{-2} \pm 2.31 \times 10^{-3}$	0.90	0.973	0.901	39.74/39.86

$[a_1]$ = Non-dimensional. $[a_2]$ = day^{-1}.

the best fit for chisel plowing with R^2, d-index and ME of 0.97, 0.992 and 0.969, respectively, while the worst fit occurred for the HO treatment fluxes with 0.88, 0.962 and 0.875 for R^2, d-index and ME, respectively. In experiment II, R^2 values were between 0.84 and 0.91 for the emissions after tillage treatments R153-U and R122-U, respectively. All of the d-index and ME values were close to 1 suggesting high accuracy of the model.

Observed (obs) and predicted (pred) values of soil C-CO_2 emissions in the no-till (NT) and tilled plots are presented in Fig. 2a and b (experiment I), and Fig. 3a and b (experiment II). In Fig. 2, the predicted emissions in the tilled plots fluctuated similarly to NT emission suggesting that tillage-induced emissions mimic fluctuations due to the changes in soil temperature and soil moisture of the NT treatment. The sharp decrease in C-

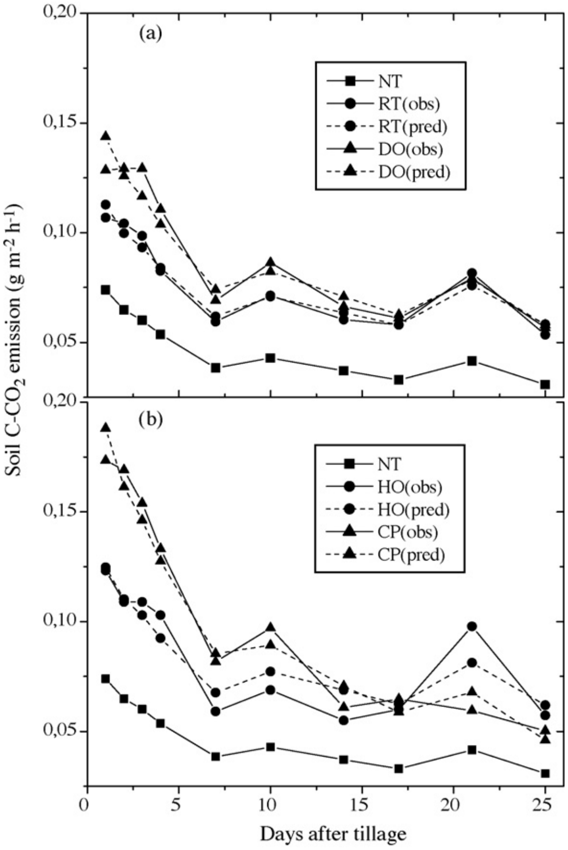

Fig. 2. Soil C-CO_2 emission for all studied treatments in experiment I (Table 1). Curves are separated into (a) and (b) parts, for clarity. Observed and predicted curves are presented by solid and dot lines, respectively.

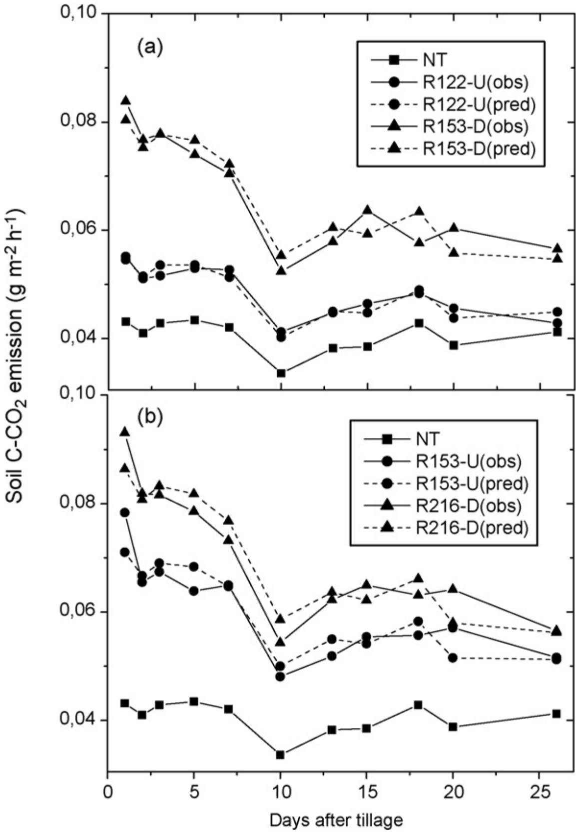

Fig. 3. Soil C-CO_2 emission for all studied treatments in experiment II (Table 1). Curves are separated into (a) and (b) parts, for clarity. Observed and predicted curves are presented by solid and dot lines, respectively.

CO_2 emission after tillage is modeled well by the a_1 amplitude and the exponential function in Eq. (10) that models different initial flux values and decay of all curves shortly after tillage. In experiment I (Fig. 2a and b), the small peak observed 10 days after tillage was probably due to an increase in soil temperature, while the other small peak at day 21 was likely due to a minor precipitation event (approximately 1 mm) the day before. In experiment II (Fig. 3a and b), the fluctuations observed in the soil C-CO_2 loss after tillage were mostly due to fluctuations in soil temperature, as no precipitation occurred during the 26 days of experiment. In experiment II, tilled emissions were linearly correlated with soil temperature in all treatments (La Scala et al., 2005), however, the coefficients of determination (R^2) were between 0.53 and 0.76, much lower than for the results obtained here utilizing no-till emissions in the prediction of emissions on the tilled plots. A similar work was done by Ellert and Janzen (1999) that presented an empirical description of tilled minus undisturbed flux by assuming this was equal to an exponential equation as function of time after tillage. Our equation was derived using a theoretical approach based on aspects related to the tillage effect on soil C that have been observed in literature, like soil C release from aggregates and the change in decay factor after tillage.

Fig. 4a–d presents the observed versus predicted scatter plots and regression lines for experiments I and II. Linear regression of observed versus predicted values showed that regression slopes were not significantly different from 1 and intercepts were not significantly different from 0 ($p < 0.05$) in all cases, with an exception to the slope of HO regression (experiment I).

Estimated a_1 and a_2 parameters ± standard error together with total emission after treatments (observed and predicted) are presented in Tables 2 and 3. All estimated parameters were significant ($p < 0.01$) and higher emissions yielded larger a_1 and a_2 parameters in each experiment. This was expected since C released from aggregates and mineralization in soils after tillage should result in higher a_1 and a_2 parameters. When observed and predicted total emissions are compared (Tables 2–5), it is possible to notice a small deviation when values are compared for each tillage treatment.

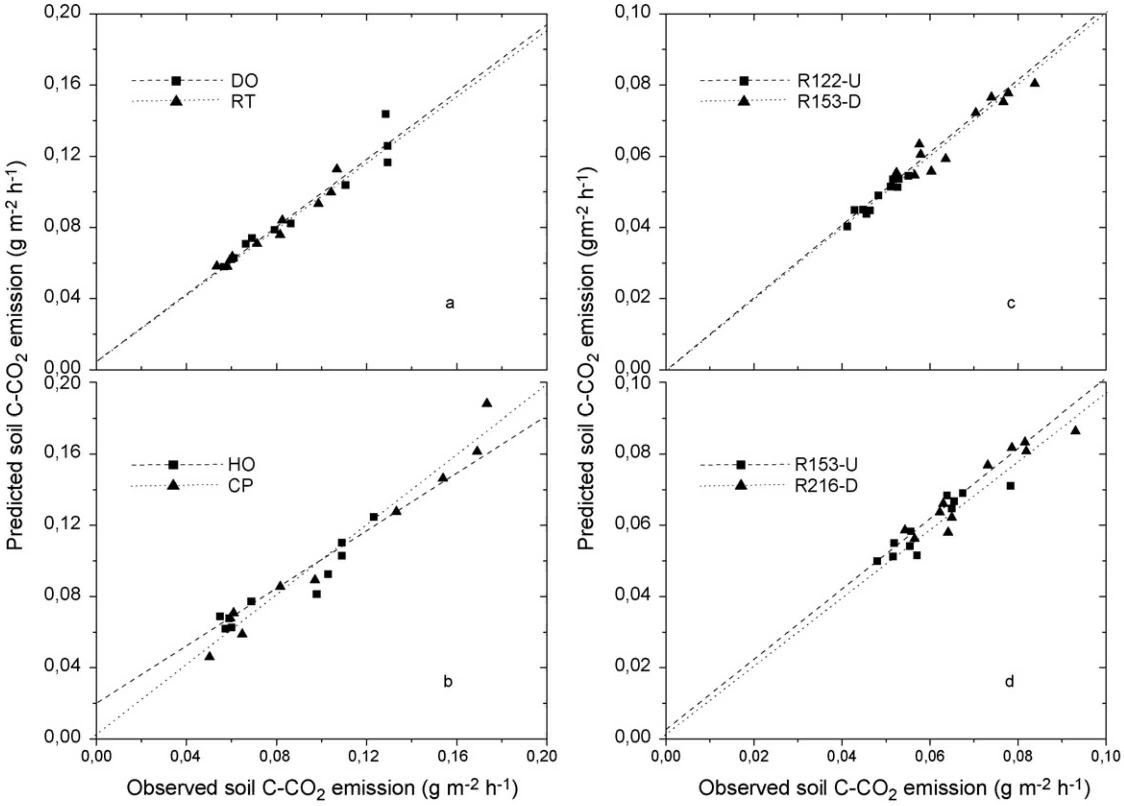

Fig. 4. Predicted vs. observed soil C-CO_2 emissions for all treatments in experiments I and II (Table 1). Plots for each experiment are separated into two parts for clarity: experiment I (a and b), experiment II (c and d).

Table 4
Estimated model parameters ± standard error, R^2, d-index, ME and total emissions (observed/predicted) of experiment III (Table 1)

Treatment	Model $F_T = a_1 F_{NT} e^{-a_2 t}$	R^2	d-index	ME	Total emission obs./pred (gC CO$_2$ m^{-2})
CP	$a_1 = 1.76 \pm 1.10 \times 10^{-1}$, $a_2 = 3.24 \times 10^{-3} \pm 5.84 \times 10^{-3a}$	0.74	0.913	0.744	244.21/240.63
MP	$a_1 = 2.14 \pm 1.45 \times 10^{-1}$, $a_2 = -1.52 \times 10^{-2} \pm 5.16 \times 10^{-3}$	0.64	0.908	0.643	371.57/378.70

$[a_1]$ = Non-dimensional. $[a_2]$ = day^{-1}.
[a] Non-significant at $p > 0.01$.

Table 5
Estimated model parameters ± standard error, R^2, d-index, ME and total emission (observed/predicted) of experiment IV (Table 1)

Treatment	Model $F_T = a_1 F_{NT} e^{-a_2 t}$	R^2	d-index	ME	Total emission obs./pred (gC CO$_2$ m^{-2})
MP	$a_1 = 2.22 \pm 2.08 \times 10^{-1}$, $a_2 = -1.84 \times 10^{-3} \pm 2.85 \times 10^{-3a}$	0.70	0.892	0.702	675.68 / 685.00

$[a_1]$ = Non-dimensional. $[a_2]$ = day^{-1}.
[a] Non-significant at $p > 0.01$.

The a_1 values derived from experiment I ranged from 1.51 to 2.60, with a 72% increase from RT to CP. In experiment II, a_1 changed from 1.27 to 2.03, a 60% increase from RT with the lower rotor rotation and rear shield up (R122-U) to the higher rotation having the rear shield lowered (R216-D). This is in accordance with Studdert and Echeverria (2000) that showed that tillage intensity would determine the extent of the effect of tillage on soil organic carbon. As a_1 relates to the amount of aggregate protected C that became unprotected after tillage, we should expect that changes would occur with different tillage equipment. These changes in a_1 would be expected to be greater than in experiment II, where differences in soil C-CO$_2$ losses were compared for different adjustments of the same tillage equipment. In studying changes in aggregate protected C in cropland (Jacinthe and Lal, 2005), results showed that, despite the high amounts of protected C in no-tillage, there was almost negligible protected C amounts after tillage, with no significant differences between chisel and moldboard treatments. Our results indicate significant changes in a_1 when comparing different tillage (systems) or adjustments within the same tillage (system).

A similar effect is observed for a_2 determined from both experiments (I and II, Tables 2 and 3). Changes were much larger in experiment I than experiment II. The a_2 values in experiment I ranged from -8.97×10^{-3} to 2.22×10^{-2} day^{-1}. In experiment II, a_2 ranged from 5.98×10^{-3} to 1.54×10^{-2} day^{-1}. In experiment I, the treatments that resulted in smaller total emissions had slightly negative a_2 values, -8.97×10^{-3} and -7.29×10^{-3} day^{-1} for RT and HO treatments, respectively. This suggests a decay factor after tillage (k_T) smaller than that for a no-till treatment (k_{NT}), as $a_2 = k_T - k_{NT}$. The decay coefficient is commonly determined by isotopic techniques (Balesdent et al., 1990; Balesdent and Balabane, 1992; Gregorich et al., 1995) or more recently by measuring the changes of soil C stocks throughout years (Bayer et al., 2006). On an annual basis, we should expect the decay coefficient for tilled plots to be higher than in the no-till condition. However, predicting the decay coefficient may be a more complex task, especially shortly after tillage because of the short-term changes in soil moisture and temperature (Stevenson and Cole, 1999). Higher soil gas diffusion and convection after tillage should cause immediate reductions in soil moisture (La Scala et al., 2006; Calderon and Jackson, 2002; Ellert and Janzen, 1999; Fortin et al., 1996) that could limit microbial activity resulting in a decrease in the decay constant, especially in drought conditions. Franzluebbers et al. (1995) reported that tillage caused disruption and mixing of the soil that allowed soil to dry more rapidly during the first days after tillage. In experiment I, just a small precipitation event of approximately 1 mm occurred during the 30-day period studied, with drought conditions in the region over the period of the experiment (La Scala et al., 2001). A drought effect was not observed in experiment II, with all a_2 parameters positive, despite this study being conducted during the same time of year (July–August, 2002). The soil moisture was more favorable in experiment II and soil C-CO$_2$ emissions were linearly correlated with soil temperature.

In order to evaluate the general applicability of the model, we applied it to two additional experiments, III and IV, conducted in Southern Brazil and Northern USA, respectively. As opposed to experiments I and II,

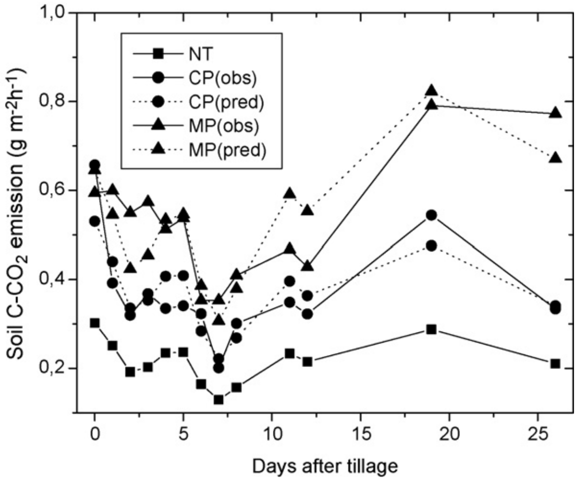

Fig. 5. Soil C-CO_2 emission for all studied treatments in experiment III (Table 1). Observed and predicted curves are presented by solid and dot lines, respectively.

which were conducted on bare fallow soils, experiments III and IV were more realistic in terms of agriculture production because seedling had occurred and vegetation cover had begun to appear during the experiment. Also, experiment III had a large amount of sugar cane crop residues incorporated by tillage near the soil surface (17 t of dry mass ha^{-1}).

The parameters determined from experiments III and IV are presented in Tables 4 and 5, while soil C-CO_2 predicted and observed curves are presented in Figs. 5 and 6, respectively. The model applied to experiment III had coefficients of determination (R^2) of 0.64 for moldboard plow and 0.74 for chisel plow. These values were higher than for the earlier published estimates for this experiment (La Scala et al., 2006), where a linear model of MP soil CO_2 flux with soil moisture had an R^2 of 0.35, and a multiple linear regression between soil CO_2 flux as dependent on soil moisture and soil temperature had an R^2 of 0.36. Comparing the determination coefficients found after applying our model to data with the ones found when trying to fit soil CO_2 fluxes with soil temperature and soil moisture we conclude that describing temporal variability of tilled surface fluxes by using no-till emissions as reference is a better method. This concept is confirmed in a longer term experiment IV, with a total period of 84 days. Emission fluctuations were satisfactorily explained by applying Eq. (10) to the data (Fig. 6) with a coefficient of determination lower than for experiments I and II, but higher than the ones obtained using soil temperature or soil moisture ($R^2 = 0.70$) in La Scala et al., 2006. Fig. 7 presents the scatter plots and regression lines of observed versus predicted values for experiments III

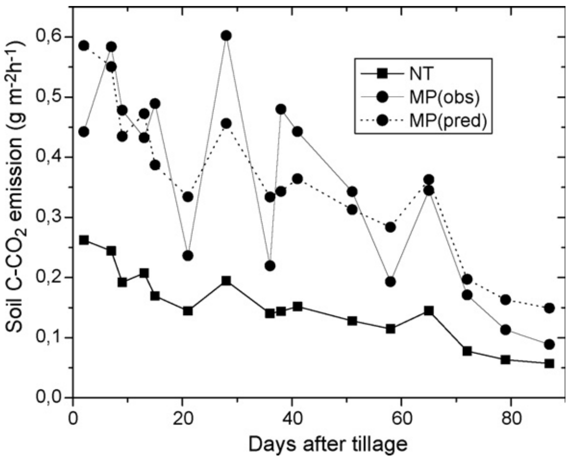

Fig. 6. Soil C-CO_2 emission for all studied treatments in experiment IV (Table 1). Observed and predicted curves are presented by solid and dot lines, respectively.

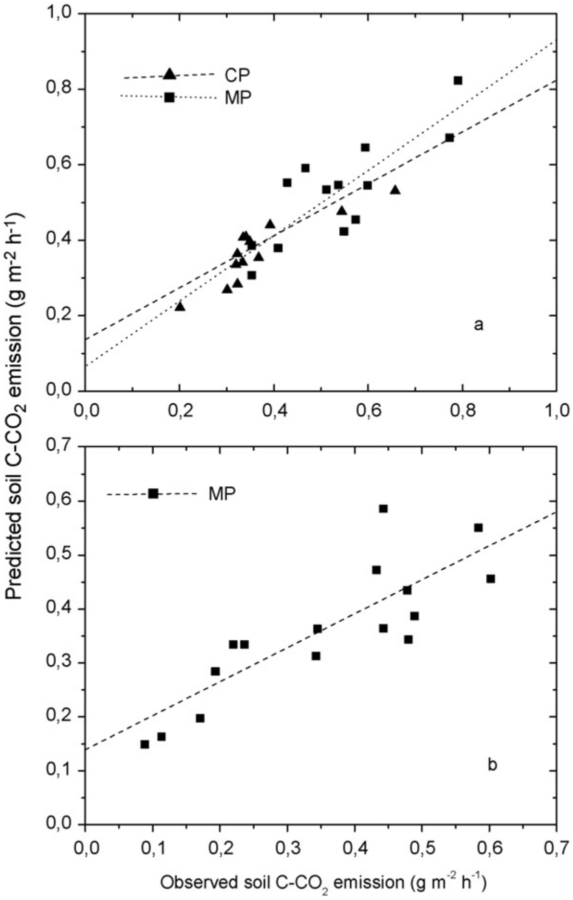

Fig. 7. Predicted vs. observed soil C-CO_2 emissions for all treatments in experiment III and IV (Table 1). Plots separated into two parts for clarity: experiment III (a) and experiment IV (b).

(Fig. 7a) and IV (Fig. 7b). Also, it is possible to notice that the estimated total emissions are quite close to the observed total emission values in all cases. Regression line slopes and intercepts were not significantly different from 0 and 1 ($p < 0.05$), respectively, for CP treatment (experiment III) and MP treatment (experiment IV).

Comparing the parameters a_1 and a_2 obtained for experiments III and IV with those determined in experiments I and II shows the parameters are within the same range. In experiment III, a_1 was 1.76 and 2.14, while the a_2 estimate was 3.24×10^{-3} and $-1.52 \times 10^{-2}\ \mathrm{day}^{-1}$ for CP and MP, respectively. In the case of experiment IV, MP resulted in $a_1 = 2.22$ and $a_2 = -1.84 \times 10^{-3}\ \mathrm{day}^{-1}$, respectively. This suggests that such parameters could have a valid range that might be observed for other tillage systems and environmental conditions. For the four experiments modeled, we found ranges for a_1 between 1.27 and 2.60 and a_2 ranged between -1.52×10^{-2} and $2.2 \times 10^{-2}\ \mathrm{day}^{-1}$. Additional experiments should be conducted and modeled to determine the range and variability of these parameters.

4. Conclusions

A model was developed to describe short-term soil C-CO_2 losses after tillage. The model uses the assumption that C decay in readily decomposable organic matter follows a first-order equation both in the tilled and no-till plots. In the tilled plot, an additional labile *C* component is introduced to the decay process due to aggregate disruption and exposure of protected organic matter to microbial activity. Predicted and observed flux values show reasonable agreement in all experiments, especially in bare fallow soils. Using a non-linear function, it was possible to predict the emissions from tilled plots better than with models based on soil temperature and soil moisture variability. Despite it is currently unknown if the tillage-induced increase is consistent across many more experiments the results presented here suggest that tillage induced C-CO_2 loss could be described by a single analytical function that takes into account no-till emission as a reference.

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