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Short-term temporal changes of bare soil CO_2 fluxes after tillage described by first-order decay models

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Summary

To further understand the impact of tillage on carbon dioxide (CO_2) emission, we compare the performance of two conceptual models that describe CO_2 emission after tillage as a function of the non-tilled emission plus a correction resulting from the tillage disturbance. The models assume that C in the readily decomposable organic matter follows a first-order reaction kinetics equation as $\frac{dC_{soil}(t)}{dt} = -kC_{soil}(t)$ 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) and k is the decay constant (time^{-1}). Two possible relationships are derived between non-tilled (F_{NT}) and tilled (F_T) soil fluxes: $F_T = F_{NT} + a_1\ e^{-a_2 t}$(model 1) and $F_T = a_3 F_{NT}\ e^{-a_4 t}$ (model 2), where t is time after tillage. The difference between these two models comes from an assumption related to the k factor of labile C in the tilled plot and its similarity to the k factor of labile C in the non-till plot. Statistical fit of experimental data to conceptual models showed good agreement between predicted and observed CO_2 fluxes based on the index of agreement (d-index) and with model efficiency as large as 0.97. Comparisons reveal that model 2, where all C pools are assigned the same k factor, produces a better statistical fit than model 1. The advantage of this modelling approach is that temporal variability of tillage-induced emissions can be described by a simple analytical function that includes the non-tilled emission plus an exponential term, which is dependent upon tillage and environmental conditions.

Introduction

Atmospheric carbon dioxide (CO_2) concentration has increased dramatically in the last 150 years, primarily because of fossil fuel combustion and cement production, with a net emission rate of 6.3 ± 0.4 Pg C year^{-1}. Land use activities had an emission rate of 1.6 ± 0.8 Pg C year^{-1} during the 1990s (Houghton *et al.*, 2001). Land use activities have contributed to increases in atmospheric-CO_2 concentration; however, the uncertainties in this balance are large, because of the complexity of gas exchange estimation over large areas and the variety of agricultural activities. Agricultural-related activities such as deforestation, soil tillage and liming are the main causes of a decrease in soil carbon (C) associated with an increase in decomposition (Schlesinger, 1999; Read *et al.*, 2001).

Tillage-induced soil C loss has been shown to be important especially over short periods (Reicosky & Lindstrom, 1993; Ellert & Janzen, 1999; Rochette & Angers, 1999; Prior *et al.*, 2000; La Scala *et al.*, 2001, 2006). 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 within aggregates to unprotected readily decomposable organic matter (Six *et al.*, 1999). Tillage also reduces bulk density, thereby increasing total porosity, promoting gas diffusion and convection, which subsequently leads to improved oxygen, temperature and moisture contents required for rapid decomposition (Sartori *et al.*, 2006). Tillage-induced CO_2 emission is primarily related to decay of light fraction (LF) organic matter, or of labile C, which has a more rapid turnover than total soil C (Wander *et al.*, 1994; De Gryze *et al.*, 2004). In recent work, Grandy & 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 (Bronick & Lal, 2005; Jacinthe & Lal, 2005; Wright & Hons, 2005), which, coupled with increases in soil temperature

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and other environmental changes, accelerates soil organic matter (SOM) decomposition (Grandy *et al*., 2006). Certainly, understanding how tillage affects soil CO_2 flux should include effects of tillage on increasing in unprotected fresh soil C as well as a tillage-induced change in the decay rate of SOM decomposition in soil.

In bare soils, measurement of CO_2 exchange is a measure of the rate of SOM decomposition as result of microbial respiration, because no root activity exists. La Scala *et al*. (2001) 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. The similarity in the temporal trends among the NT and tillage treatments, presumably in response to temperature, water content and other physical changes, suggests that the NT emission could be used as a baseline to predict CO_2 emissions after tillage. Observations where emission fluctuations (increases and decreases) after tillage are mimicked in the non-tilled curves have been reported by several authors (Reicosky & Lindstrom, 1993; Franzluebbers *et al*., 1995; Fortin *et al*., 1996; Prior *et al*., 1997; Rochette & Angers, 1999; La Scala *et al*., 2001, 2005, 2006). Our hypothesis is that an additional amount of readily decomposable organic matter (labile C) is made available to the soil organisms by tillage (C_T), exposing aggregate-protected C to air and microorganisms. The soil C-CO_2 flux in tilled plots can be described as the result of a natural plus a tillage-induced emission. Emissions from tilled treatments are addressed in terms of the NT emission plus a tillage-induced component, assuming labile C in SOM decays following a first-order differential equation. Temporal variability of tillage-induced emissions can be described by a single analytical function that includes NT emission plus an exponential term in time, modulated by tillage and environmentally dependent characteristics.

The proposed models

A conceptual representation of the physical aspects included in our model is described in Figure 1. First, we consider that the amount of labile C in unprotected and readily decomposed SOM in the T plot ($C_{NT} + C_T$) is greater than in the NT plot (C_{NT}) because of that resulting from aggregate fracture after tillage (C_T). Furthermore, the soil layer in the tilled plot is assumed to be less dense and with a soil structure that is favourable for gas diffusion and convection. Initially, fluxes in both NT and T plots are proportional to the rate of labile C decay in the unprotected SOM: $F_{NT} \propto \frac{dC_{NT}}{dt}$ and $F_T \propto \frac{dC_{NT}}{dt} + \frac{dC_T}{dt}$, respectively. We prefer to address fluxes in terms of C transported by CO_2, instead of CO_2, because C fluxes are directly related to the C decay (mass) in soil. The model assumes that soil C decay follows a first-order reaction kinetics equation as:

$$\frac{dC_{soil}(t)}{dt} = -kC_{soil}(t), \quad (1)$$

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

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

where $C_{soil}(t)$ 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) will be assumed here as constant: this is justified by the short-term nature of the field experiment (1 month). Typically, k is described in the literature as an exponential and logarithm dependent on soil temperature and soil moisture, respectively (Parton *et al*., 1994). Equation (2) shows that with no additional soil C input, the initial amount of available labile C (C_0) should decay exponentially with time controlled by the decay constant (k).

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

$$F(t) \propto -\frac{dC_{soil}(t)}{dt}. \quad (3)$$

Substituting Equation (3) in Equation (2) above yields:

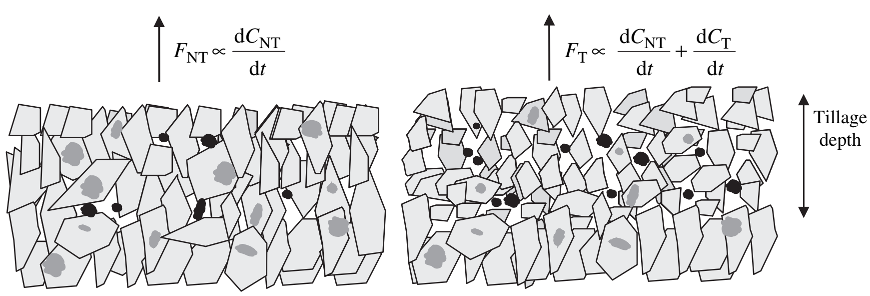

Figure 1 Schematic representation of free (black) and aggregate protected (grey) labile C in the no-till (left) and tilled (right) plots after tillage. Tillage releases C from aggregates resulting in an increase of labile C available for microbial decay.

$$F(t) \propto -\frac{dC_{\mathrm{soil}}(t)}{\mathrm{dt}} = -\frac{\mathrm{d}}{\mathrm{d}t}(C_0\mathrm{e}^{-kt})$$

$$F(t) \propto C_0 k\mathrm{e}^{-kt}.$$

The relationship above is presented as proportionality but we will assume equality because microbial biomass contributes to the decay process after microbes die. The decay constant (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 (Equation 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 and (b) a change in k resulting from changes in soil physical properties caused by tillage. The assumption is 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 pool present 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_T (t = 0) is the total unprotected labile C immediately after tillage and equates to the unprotected labile C available before tillage (i.e. for a NT plot) plus the tillage-induced component (C_{0T}). Thus, at any time (t) after tillage, the amount of labile C in tilled soil follows Equation (5):

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

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

$$\begin{aligned} F_{\mathrm{T}}(t) &= -\frac{\mathrm{d}C_{\mathrm{soil}}}{\mathrm{d}t} = -\frac{\mathrm{d}}{\mathrm{d}t}(C_{\mathrm{NT}} + C_{\mathrm{T}}) \\ &= -\frac{\mathrm{d}C_{\mathrm{NT}}}{\mathrm{d}t} - \frac{\mathrm{d}C_{\mathrm{T}}}{\mathrm{d}t}. \end{aligned} \tag{6}$$

Model 1

Model 1 is derived by assuming that labile C in the tilled plot is composed of two different pools having different k factors, k_{NT} and k_T. Hence, C-CO_2 flux from tilled plot should be derived by:

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

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

$$F_{\mathrm{NT}}(t) = C_{0\mathrm{NT}}k_{\mathrm{NT}}\mathrm{e}^{-k_{\mathrm{NT}}t}, \text{therefore:}$$

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

$$\text{If } a_1 = C_{0\mathrm{T}}k_{\mathrm{T}} \text{ and } a_2 = k_{\mathrm{T}}$$

$$\text{then: } F_{\mathrm{T}}(t) = F_{\mathrm{NT}}(t) + a_1\,\mathrm{e}^{-a_2 t}(\text{Model 1}). \tag{7}$$

Equation (7) describes the emission after tillage as function of NT emission added to an exponential decay term in time. This form of expression has been already considered by others (e.g. Ellert & Janzen, 1999) who considered the exponential decay aspect of emission after tillage curves. Both parameters have physical meanings, $a_1 = C_{0T}k_T$ and $a_2 = k_T$; this would indicate that the decay constant of labile C induced by tillage in the tilled plot would be changing from a half-life time ($t_{1/2}$) that would be equal to $t_{1/2} = 1/a_2 \ln(2)$. Further, by dividing a_1/a_2, we could estimate the amount of labile C made available to microbial activity after tillage (C_{0T}) immediately afterwards.

Model 2

Model 2 is derived by using another assumption (i.e. that in the tilled plot all the labile C is associated with a k-factor (k_T) that is different from the NT plot). Therefore, the soil C-CO_2 flux would be given by:

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

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

Multiplying the above equation by the NT C-CO_2 flux, we have:

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

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

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

At this point we have 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 NT soil by a factor b_T, which is likely to be >1. It is important to note that b_T will also depend on the form of the tillage used (index T). If we substitute $k_T = b_T k_{NT}$ into the equation above we get :

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

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

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

If we define

$$a_3 = b_T\left(\frac{C_{0NT} + C_{0T}}{C_{0NT}}\right)$$

and

$$a_4 = (b_T - 1)k_{NT} = k_T - k_{NT}$$

we have:

$$F_T = a_3 F_{NT}\ e^{-a_4 t}\ (\text{Model 2}). \qquad (10)$$

The expressions in Equations 7 and 10 describe the emissions after tillage as functions of the NT emission and time, once parameters a_1 and a_2 (in model 1) and a_3 and a_4 (in model 2) are known for bare soils, where the sole C emission is from microbial activity alone. a_1 is related to the additional labile C induced by tillage and the decay constant in the tillage plot ($C_{0T}k_T$), while the a_2 parameter is equal to the decay constant in the tilled plot (k_T).

A_3 is related to how much labile C was induced by tillage into the decay process (C_{0T}) and how the decay constant was altered by the tillage event (b_T). The a_4 factor is equal to the difference between the tilled and NT plot decay constants, while a_3 is also dependent on the ratio between total labile C in the tilled plot relative to the NT one. Currently, both models account for C emissions that are derived from soil C decay and do not include root respiration.

The objective of our paper is to compare these two models based on emissions from non-disturbed soils to predict C losses after tillage.

Materials and methods

The two models were applied to data obtained from an experiment conducted in 2000 on a red latosol in southern Brazil. This experiment was carried out at the experimental farm of the FCAV/UNESP campus, on a soil that is currently used for intensive practices, involving wheat, soya beans and sugarcane crops, and having a soil C content of, typically, 11 g kg^{-1}. Carbon dioxide flux measurements were performed using a commercial IRGA (infrared gas analyser) (LI-6400, LiCor, NE). The detailed experimental procedures used for CO_2 emission measurements can be found in La Scala *et al.* (2001) who tested the effect of four different tillage systems on emissions. These were: RT, rotary tiller, one pass with rotor rotation of 172 r.p.m. CP, chisel plough, one pass; DO, reversible disc plough followed by offset disk harrow; and HO, heavy offset disc harrow, one pass followed by offset disc harrow. The experiments included a non-tilled reference treatment (NT), where CO_2 flux was also monitored.

Statistica software (StatSoft Inc, 2001) was used to fit the experimental data to the model by using non-linear least square estimation with the Gauss-Newton method for generating the estimated a_1, a_2, a_3 and a_4 parameters. During the data fitting process, parameter values were initially set to zero, and the number of iterations before getting the final parameters values was not higher than 10 in any case.

The models were further evaluated by comparing model-predicted with observed values by using the index of agreement (d-index) and modelling efficiency (ME). These two indexes when presented together represent an improvement over R^2 for model evaluation as these are sensitive to differences in the observed and model-predicted means (Legates & McCabe, 1999). The index of agreement (d-index) was calculated with the following expression:

$$d = 1 - \frac{\sum_{t=1}^{n}\left(F_t^{obs} - F_t^{pred}\right)^2}{\sum_{t=1}^{n}\left(|F_t^{obs} - \bar{F}^{obs}| + |F_t^{pred} - \bar{F}^{obs}|\right)^2}, \qquad (11)$$

where F_t^{obs} is the observed emission at an specific time after tillage t, with a mean emission throughout the experiment as $\bar{F}^{obs}$, and F_t^{pred} is the predicted emission at that time t (Willmott, 1981; Mayer & Butler, 1993; Legates & McCabe, 1999). The value of the d-index 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:

$$ME = 1 - \frac{\sum_{t=1}^{n}\left(F_t^{obs} - F_t^{pred}\right)^2}{\sum_{t=1}^{n}\left(F_t^{obs} - \bar{F}^{obs}\right)^2}, \qquad (12)$$

where F_t^{obs}, $\bar{F}^{obs}$ and F_t^{pred} have the same meanings as described above (Mayer & Butler, 1993; Legates & McCabe, 1999). Model efficiency will vary between minus infinity and 1, with higher values (closer to 1) indicative of superior performance. Comparisons were made for measured emissions at each time after tillage versus results predicted by the models.

Results and Discussions

Results of modelling soil C-CO_2 emission by fitting experimental data with model 1 (Equation 7) and model 2 (Equation 10) are presented in Tables 1 and 2, respectively. The d-index and *ME* for all treatments show good agreement between observed and predicted values for both models. Experimental data for chisel ploughing had the best fit with *ME* values of 0.966 and 0.969 when model 1 and model 2 were applied to the data, respectively. The worst fit occurred for the HO treatment fluxes with *ME* indexes of 0.831 and 0.875 for model 1 and model 2, respectively. The d-indexes were also good (e.g. 0.965 and 0.983 for models 1 and 2, respectively for DO data). When d-indexes and *ME*s from models 1 and 2 are compared, model

Table 1 Estimated parameters ± standard error, d-index and *ME* after application of model 1 to experimental data

Treatment	Model, $F_T = F_{NT} + a_1 e^{-a_2 t}$	d-index	*ME*
RT	$a_1 = 3.34 \times 10^{-2} \pm 3.92 \times 10^{-3}$		
	$a_2 = 1.05 \times 10^{-2} \pm 9.88 \times 10^{-3}$	0.912	0.893
HO	$a_1 = 4.40 \times 10^{-2} \pm 7.97 \times 10^{-3}$		
	$a_2 = 1.90 \times 10^{-2} \pm 1.66 \times 10^{-2}$	0.831	0.754
DO	$a_1 = 6.39 \times 10^{-2} \pm 5.97 \times 10^{-3}$		
	$a_2 = 4.09 \times 10^{-2} \pm 1.08 \times 10^{-2}$	0.965	0.914
CP	$a_1 = 1.15 \times 10^{-1} \pm 7.35 \times 10^{-3}$		
	$a_2 = 9.03 \times 10^{-2} \pm 1.19 \times 10^{-2}$	0.990	0.966

$[a_1]$ = g C-CO_2 m^{-2} h^{-1}. $[a_2]$ = day^{-1}.
CP, chisel plough, one pass, 5 shanks with 1.5 depth/spacing ratio; DO, reversible disc plough followed by offset disc harrow; HO, heavy offset disc harrow, one pass followed by offset disc harrow; RT, rotary tiller, one pass with rotor rotation of 172 r.p.m. raised rear shield.

2 performs slightly better than model 1. In model 2, we assume that both labile C pools in the tilled plot, the one that was there before tillage and the one induced by tillage operation, are assigned the same decay constant (k_T).

Observed (obs) and predicted (pred) values derived from models 1 and 2 of soil C-CO_2 emissions in the NT and tilled soils for RT, DO and HO treatments are presented in Figures 2–4, respectively. The predicted emissions in the tilled plots fluctuated over time in a similar way to NT emission, suggesting that these are sensitive to changes in soil temperature and moisture. The sharp decrease in C-CO_2 emission after tillage is modelled well by the a_1 and a_3 amplitudes (models 1 and 2, respectively), while the exponential function models the decay of all curves shortly after tillage modelled by a_2 and a_4 for models 1 and 2, respectively. The small peak observed 7 days after tillage results from an increase in soil temperature as measured at the time of measurement. The other small peak at

Table 2 Estimated parameters ± standard error, d-index, *ME* after application of model 2 to experimental data

Treatment	Model $F_T = a_3 F_{NT} e^{-a_4 t}$	d-index	ME
RT	$a_3 = 1.51 \pm 3.72 \times 10^{-2}$		
	$a_4 = -8.97 \times 10^{-3} \pm 2.29 \times 10^{-3}$	0.989	0.958
HO	$a_3 = 1.67 \pm 8.44 \times 10^{-2}$		
	$a_4 = -7.29 \times 10^{-3} \pm 4.78 \times 10^{-3}$	0.962	0.875
DO	$a_3 = 1.95 \pm 7.09 \times 10^{-2}$		
	$a_4 = 1.37 \times 10^{-3} \pm 3.84 \times 10^{-3}$	0.983	0.935
CP	$a_3 = 2.60 \pm 8.69 \times 10^{-2}$		
	$a_4 = 2.22 \times 10^{-2} \pm 4.52 \times 10^{-3}$	0.992	0.969

$[a_3]$ = non-dimensional. $[a_4]$ = day^{-1}.
CP, chisel plough, one pass, 5 shanks with 1.5 depth/spacing ratio; DO, reversible disc plough followed by offset disc harrow; HO, heavy offset disk harrow, one pass followed by offset disc harrow; RT, rotary tiller, one pass with rotor rotation of 172 r.p.m. raised rear shield.

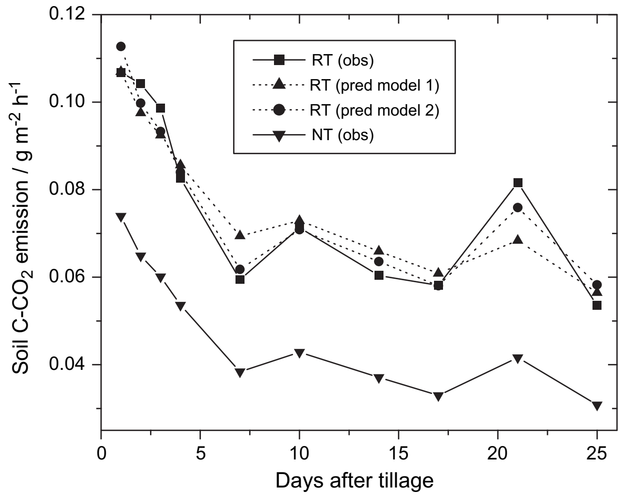

Figure 2 Soil C-CO_2 emission for RT treatments in experiment. Observed and predicted curves (models 1 and 2) are presented by solid and dotted lines, respectively. RT, rotary tiller, one pass with rotor rotation of 172 r.p.m. raised rear shield. NT, non-tilled.

day 21 was probably after a minor precipitation event (approximately 1 mm) the day before measurement (La Scala *et al.*, 2001). At both times, model 2 is better than model 1 in mimicking the natural oscillations. Model 2 was derived using a theoretical approach that takes into account the tillage effect that has been observed when soil C is released from aggregates and there is a change in the decay constant. Nevertheless, we consider that model 1 would be better when applied to a tillage event that introduces a labile C source having a different decay constant (e.g. the incorporation of a fresh crop residue).

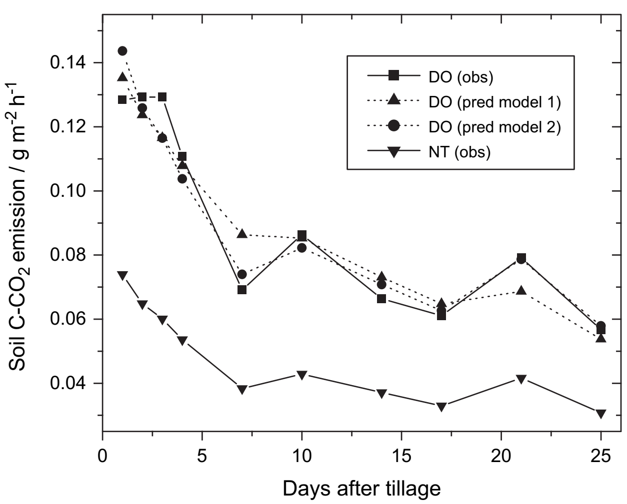

Figure 3 Soil C-CO_2 emission for DO treatments in experiment. Observed and predicted curves (models 1 and 2) are presented by solid and dotted lines, respectively. DO, reversible disc plough followed by offset disc harrow. NT, non-tilled.

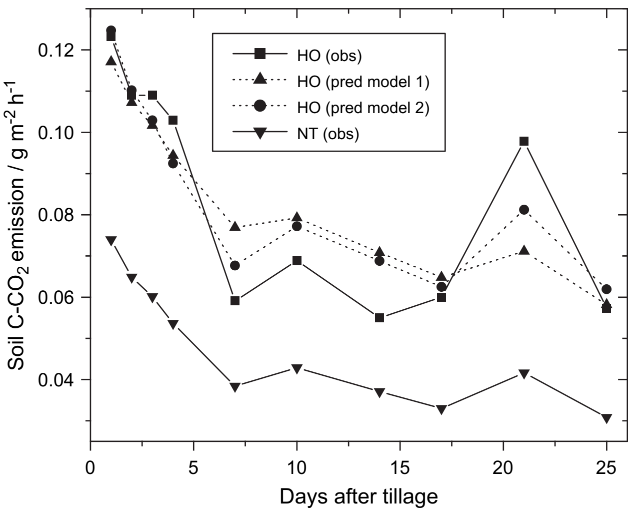

Figure 4 Soil C-CO_2 emission for HO treatments in experiment. Observed and predicted curves (models 1 and 2) are presented by solid and dotted lines, respectively. HO, heavy offset disc harrow, one pass followed by offset disc harrow. NT, non-tilled.

Despite the better performance of model 2, the estimated a_1 and a_2 parameters are important, as those may have physical interpretations. The a_1 values ranged from 3.34×10^{-2} to 1.15×10^{-1} g C-CO_2 m^{-2} h^{-1}, while a_2 ranged from 1.05×10^{-2} to 9.03×10^{-2} day^{-1} from RT to CP, respectively (Tables 1, 2). This would indicate labile C loss induced by tillage had a half-life ($t_{1/2}$) equal to $1/a_2 \ln(2)$ in the tilled plot. Therefore, estimated $t_{1/2}$ would be changed from 66 to 7.7 days for RT and CP, respectively. Also, a_1/a_2 should be equal to C_{0T} (i.e. the amount of labile C induced by tillage available to microbial activity immediately after tillage). Based on a_1 and a_2 parameters, such values would range from 30.6 to 76.3 g C m^{-2} after RT and CP operations. This is in accordance with Studdert & Echeverria (2000), who showed that tillage intensity would affect soil organic C. As a_1/a_2 relates to the amount of aggregate-protected C that became unprotected after tillage, we should expect that changes would occur with different tillage equipment. Increasing a_1 and a_2 values are directly related to the increase in total emission caused by tillage implements.

Model 2 parameter a_3 changed from 1.51 to 2.60 (non-dimensional). Despite large amounts of protected C in NT cropland soil, there were negligible amounts of protected C after tillage, with no significant differences between chisel and mouldboard plough treatments (Jacinthe & Lal, 2005). Our results indicate significant changes in a_3 when comparing different tillage systems. A similar effect is observed for a_4 as values ranged from -8.97×10^{-3} to 2.22×10^{-2} day^{-1}. The treatments that resulted in smaller total emissions had slightly negative a_4 values, -8.97×10^{-3} and -7.29×10^{-3} day^{-1} for RT and HO treatments, respectively. This suggests a decay constant after tillage (k_T) that is smaller than that for NT soils (k_{NT}), as $a_4 = k_T - k_{NT}$. Decay constants are commonly determined by isotopic techniques (Balesdent *et al.*, 1990; Balesdent & Balabane, 1992; Gregorich *et al.*, 1995) or more recently by measuring the changes of soil C stocks over time (Bayer *et al.*, 2006). On an annual basis, we should expect the decay constants for tilled plots to be greater than for NT conditions because of increased aeration and soil residue mixing. However, predicting the decay constant may be a more complex task especially shortly after tillage, because of short-term changes in soil moisture and temperature (Stevenson & Cole, 1999) as well as complex soil particle movement during tillage (Spokas *et al.*, 2007). Higher soil gas diffusion and convection rates after tillage should cause immediate reductions in soil moisture (Fortin *et al.*, 1996; Ellert & Janzen, 1999; Calderon & Jackson, 2002; La Scala *et al.*, 2006) that could limit microbial activity resulting in a smaller decay constant. This would be particularly likely 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. This was evident in our experiment where a small precipitation event of approximately 1 mm occurred during the 30-day period studied, with drought conditions during the experiment (La Scala *et al.*, 2001).

Conclusions

Two simple first-order decay models were developed to describe short-term soil C-CO_2 losses after tillage. In the tilled plot, an additional labile C component was introduced to the decay process because of aggregate disruption and exposure of protected organic matter to microbial activity. The models assume that C decay in readily decomposable organic matter follows a first-order equation both in the tilled and NT plots. The difference between the two models was in the assumption of similar decay constants or altered decay rates following tillage. Predicted and observed flux values show good agreement in all experiments that were conducted on bare fallow soils, but model 2, which assumes equal decay constants, performed slightly better than model 1, which had different decay constants before and after tillage. It is anticipated that different tillage implements could be assigned a range of expected values for the parameters, making the model easier to use. Using a non-linear function that takes into account the NT emission as a reference, it was possible to predict the emissions from tilled plots better without needing direct soil temperature, and possibly soil moisture variability information. Once a set of parameters has been derived after further validation, we believe that our models could be applied to predictions of short-term soil C losses after tillage.

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