FIRST-ORDER DECAY MODELS TO DESCRIBE SOIL C-CO$_2$ LOSS AFTER ROTARY TILLAGE

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ABSTRACT: To further understand the impact of tillage on CO$_2$ emission, the applicability of two conceptual models was tested, which describe the CO$_2$ emission after tillage as a function of the non-tilled emission plus a correction due to the tillage disturbance. Models assume that C in readily decomposable organic matter follows a first-order reaction kinetics equation as: $dC_{soil}(t) / dt = -k\, C_{soil}(t)$, 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 assumptions were tested to determine the tilled (F_T) fluxes: the decay constants (k) of labile soil C before and after tillage are different (Model 1) or not (Model 2). Accordingly, C flux relationships between non-tilled (F_{NT}) and tilled (F_T) conditions are given by: $F_T = F_{NT} + a_1 e^{-a_2 t}$ (model 1) and $F_T = a_3 F_{NT}\ e^{-a_4 t}$ (model 2), where t is time after tillage. Predicted and observed CO$_2$ fluxes presented good agreement based on the coefficient of determination ($R^2 = 0.91$). Model comparison revealed a slightly improved statistical fit of model 2, where all C pools are assigned with the same k constant. Rotary speed was related to increases in the amount of labile C available and to changes of the mean resident labile C pool available after tillage. This approach allows describing the temporal variability of tillage-induced emissions by a simple analytical function, including non-tilled emission plus an exponential term modulated by tillage and environmentally dependent parameters.

Key words: soil respiration, soil tillage, soil organic matter, labile carbon decay

MODELOS DE DECAIMENTO DE PRIMEIRA ORDEM APLICADO A DESCRIÇÃO DA PERDA DE C-CO$_2$ DO SOLO APÓS PREPARO COM ENXADA ROTATIVA

RESUMO: Para entendimento do impacto do preparo do solo sobre as emissões de CO$_2$ desenvolvemos e aplicamos dois modelos conceituais que são capazes de prever a emissão de CO$_2$ do solo após seu preparo em função da emissão da parcela sem distúrbio, acrescida de uma correção devido ao preparo. Os modelos assumem que o carbono presente na matéria orgânica lábil segue uma cinética de decaimento de primeira ordem, dada pela seguinte equação: $dC_{soil}(t) / dt = -k\, C_{soil}(t)$, e que a emissão de C-CO$_2$ é proporcional a taxa de decaimento do C no solo, onde $C_{solo}(t)$ é a quantidade de carbono lábil disponível no tempo (t) e k é a constante de decaimento (tempo^{-1}). Duas suposições foram testadas para determinação das emissões após o preparo do solo (F_p): a constante de decaimento do carbono lábil do solo (k) antes e após o preparo é igual (Modelo 1) ou desigual (Modelo 2). Conseqüentemente, a relação entre os fluxos de C das parcelas sem distúrbio (F_{SD}) e onde o preparo do solo foi conduzido (F_p) são dadas por: $F_P = F_{SD} + a_1 e^{-a_2 t}$ (modelo 1) e $F_P = a_3 F_{SD}\ e^{-a_4 t}$ (modelo 2), onde t é o tempo após o preparo. Fluxos de CO$_2$ previstos e observados relevam um bom ajuste dos resultados com coeficiente de determinação (R^2) tão alto quanto 0,91. O modelo 2 produz um ajuste ligeiramente superior quando comparado com o outro modelo. A velocidade das pás da enxada rotativa foi relacionada a um aumento na quantidade de carbono lábil e nas modificações do tempo de residência médio do carbono lábil do solo após preparo. A vantagem desta metodologia é que a variabilidade temporal das emissões induzidas pelo preparo do solo pode ser descrita a partir de uma função analítica simples, que inclui a emissão da parcela sem distúrbio e um termo exponencial modulado por parâmetros dependentes do preparo e de condições ambientais onde o experimento foi conduzido.

Palavras-chave: respiração do solo, preparo do solo, matéria orgânica do solo, decaimento do carbono lábil

INTRODUCTION

In Brazil, the main activity that contributes to greenhouse gas emissions is the land use management and conversion of soils in agriculture (Cerri et al., 2007; Fearnside, 2006). Soil tillage has been shown to be one of the processes that contribute to the transfer of soil carbon to atmosphere with emissions as low as zero and as high as 1990 kg C ha^{-1} produced within weeks after tillage (Alvarez et al., 2001). Despite the variability, one similarity exists: emission after tillage typically shows a huge increase followed by an exponential decay-like phase, confirmed in many soil systems all over the world (La Scala et al., 2006, La Scala et al., 2001; Prior et al., 2000; Ellert & Janzen, 1999; Rochette & Angers, 1999; Reicosky et al., 1997; Reicosky & Lindstrom, 1993). This decay-like phase has been related to the exposure of labile carbon to microbial activity, after tillage break down (Grandy & Robertson, 2007; De Gryze et al., 2006; Six et al., 1999). Moreover, tillage reduces soil density and improves gas diffusion and oxygen conditions in favor of microbial activity and decay of soil organic matter (Sartori et al., 2006; Molina et al., 1983).

The rotary tiller is one of the most used tillage implements in Brazil, especially among potato growers. Typically, blade rotation and the rear shield position are adjusted to promote higher soil fragmentation in order to achieve smaller soil aggregates and a better crop development (Salokhe & Ramalingam, 2001). This intensive soil tillage promotes reduction of soil aggregate diameters and leads to rapid soil organic matter oxidation and CO_2 flux to the atmosphere (Balota et al., 2004). Accordingly, a higher rotary tillage is expected to increase the labile soil carbon available to microbial activity and, consequently, increasing soil CO_2 emission after tillage.

Simple first-order decay models were evaluated to test whether decay constants for labile C pools before and after tillage are different. Models were tested with data of C-CO_2 emission from tropical soil after rotary tillage using different rotor rotation speeds.

MATERIAL AND METHODS

Model description

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 for a tilled (T) plot ($C_{NT} + C_T$) is higher than in a no-till (NT) plot (C_{NT}) due to the additional amount introduced due to fracture of aggregates during tillage (C_T). Furthermore, the soil layer in the tilled plot is likely to be less dense, favoring gas diffusion and convection. Initially, both fluxes in the NT and T plots are proportional to the rate of labile C decay in the unprotected SOM: $F_{NT} \alpha \frac{dC_{NT}}{dt}$ and $F_T \alpha \frac{dC_{NT}}{dt} + \frac{dC_T}{dt}$, 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 displays first-order reaction kinetics:

$$\frac{dC_{soil}(t)}{dt} = -kC_{soil}(t) \qquad (01)$$

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

$$C_{soil}(t) = C_0 e^{-kt} \qquad (02)$$

where $C_{soil}(t)$ is the available labile soil C (g m^{-2}) and k ($time^{-1}$) is the decay constant. In literature the k is described as an exponential and logarithm function depending on soil temperature and moisture (Parton et

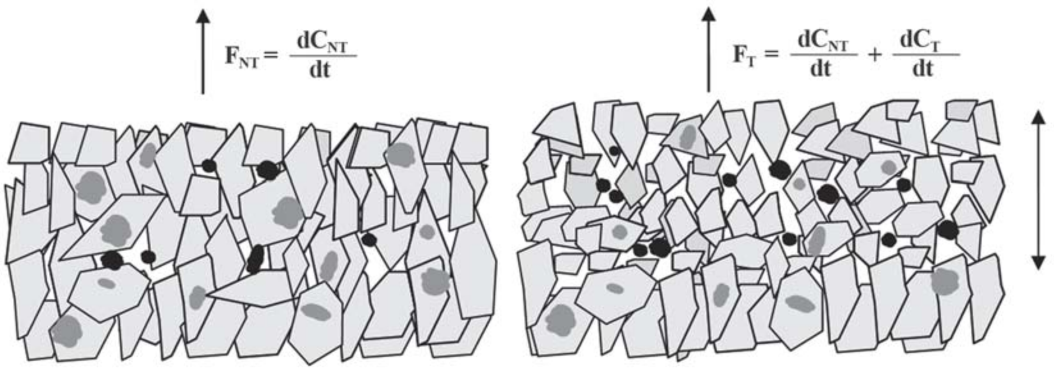

Figure 1 - Schematic representation of free (black) and aggregate protected (grey) labile C in the no-till (left) and tilled (right) plots after tillage. The arrow on the right side of the tilled plot indicates the tillage operation depth.

al., 1994). Thus, with no additional soil C input, the initial amount of available labile C in the 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 equation 02, especially in the case of bare soils. Though, not all C from organic matter decomposition is transferred immediately to CO_2, and as part of the C can be incorporated into microbial biomass (Stevenson & Cole, 1999), we assume that C emission from microbial activity is negatively proportional to the decay rate:

$$F(t) \propto -\frac{dC_{soil}(t)}{dt} \qquad (03)$$

The higher the decay rate, the higher the soil $C\text{-}CO_2$ emission. Notably, this approach does not account for C emissions that are derived from root respiration. Substituting Eq. 03 into Eq. 02 yields:

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

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

These relationships are presented as proportionalities but we will assume them as equalities because microbial biomass contributes to the decay process after microbes have died (Stevenson & Cole, 1999). The decay constant (k) estimated here will not be a decay of only one soil C component, but will include C in the microbial biomass emitted in later respiration. In any case C that is kept in the soil, even in the form of microbial biomass, will eventually decay in time (equation 1). Soil CO_2 emission, instead of $C\text{-}CO_2$, could also be described by the relationship shown above with the difference of a 12/44 factor to convert from CO_2 into C alone.

$$F(t) = C_0 k e^{-kt} \qquad (04)$$

The effect of tillage on soil CO_2 flux is described by taking into account both, additional tillage-induced C available for decay process and a change in the constant k due to changes in soil physical properties caused by tillage. We assume that after tillage (t = 0), the tillage-induced C (C_{0T}) added to the labile C (C_{0NT}) that was present there before tillage. So:

$$C_T(t = 0) = C_{ONT} + C_{0T}$$

where C_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_{0T}). So, at any time (t) after tillage, the amount of labile C in a tilled plot follows below:

$$C_{Soil}(t) = C_{NT}(t) + C_T(t) \qquad Eq.05$$

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

$$F_T(t) = -\frac{dC_{Soil}}{dt} = -\frac{d}{dt}(C_{NT} + C_T) = -\frac{dC_{NT}}{dt} - \frac{dC_T}{dt} \quad Eq.06$$

Our main motivation to develop these models is based on experiments conducted on bare soils which showed that after peak emissions CO_2 flux fluctuates close to no-till emissions suggesting the use of no-till emissions as a baseline for description of temporal variability after tillage (La Scala et al., 2001, 2005, 2006).

Model 1, different k factors in tilled plots:

Model 1 is derived by assuming labile C in the tilled plot is comprised of two different pools having different k factors (Table 1). The pools of labile C that was already in the soil before tillage has a k factor equal to the non-till plot (k_{NT}) while the k factor that was induced by the tillage event has a value k_T. Hence, the $C\text{-}CO_2$ flux from tilled plot should be derived by:

$$F_T(t) = -\frac{dC_{Soil}(t)}{dt} = -\frac{d}{dt}(C_{0NT}e^{-k_{NT}t} + C_{0T}e^{-k_T t})$$

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

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

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

If we call $a_1 = C_{0T}k_T$ and $a_2 = k_T$ we have:

$$F_T(t) = F_{NT}(t) + a_1\,e^{-a_2 t} \quad \text{(Model 1)} \qquad Eq.07$$

The above shown relationship describes the emission after tillage as function of the no-till emission added to an exponential decay term in time (Ellert & Janzen, 1999), and allows to estimate the half-life time ($t_{1/2}$) of labile C induced by tillage as $t_{1/2} = \frac{1}{a_2}\ln(2)$. The amount of labile C available for microbial activity due to tillage (C_{0T}) is defined as: $C_{0T} = \frac{a_1}{a_2}$.

Model 2, equal k factors in tilled plots:

Model 2 is derived using another assumption, i.e., in the tilled plot all the labile C is decomposed with the same k-factor (k_T, Table 1). Soil $C\text{-}CO_2$ flux would be given by:

$$F_T(t) = -\frac{dC_{Soil}(t)}{dt} = -\frac{d}{dt}(C_{0NT}e^{-k_T t} + C_{0T}e^{-k_T t})$$

$$F_T(t) = C_{0NT}\,k_T\,e^{-k_T t} + C_{0T}k_T\,e^{-k_T t}$$

Table 1 - Main definitions and differences related to models 1 and 2.

Definitions	C_{0NT}: labile C content available to microbial activity in soil before tillage	
	C_{0T}: labile C content made available to microbial activity in soil by tillage	
	k_{NT}: decay factor of labile C in no-till plot (model 1 and 2) and in tilled plot (C_{C0NT}, model 1)	
	k_T: decay factor of labile C in tilled plot (C_{0T} model 1, C0NT and C_{0T} model 2)	
Models	Model 1 $F_T = F_{NT} + a_1\, e^{-a_2 t}$	Model 2 $F_T = a_3 F_{NT}\, e^{-a_4 t}$
Main hypothesis	In tilled plot C_{0NT} and C_{0T} have different k-factors (k_{NT} and k_T, respectively)	In tilled plot C_{0NT} and C_{0T} have the same k-factor (k_T)
	In tilled plot C_{0NT} has the same k-factor of C_{0T} in no-till plot	In tilled plot k-factor of labile carbon is bT times the k-factor of C_{0NT} in no-till plot (k_T=$b_T k_{NT}$)
Parameters	$a_1 = C_{0T} k_T$	$a_3 = b_T(\frac{C_{0NT} + C_{0T}}{C_{0NT}})$
	$a_2 = k_T$	$a_4 = k_T - k_{NT}$

Multiplying and dividing by the non-tilled C-CO_2 flux, we have:

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

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

Here we assume that k_T and k_{NT} factors are proportional to each other by including b_T which is likely > 1. Thus, $k_T = b_T\, k_{NT}$. If we substitute k_T in the above equation and resolve k_{NT} in the numerator and denominator, we obtain:

$$F_T(t) = \left[\frac{C_{0NT} b_T k_{NT}\, e^{-b_T k_{NT} t} + C_{0T} b_T k_{NT}\, e^{-b_T k_{NT} t}}{C_{0NT} k_{NT}\, e^{-k_{NT} t}}\right] F_{NT}(t) \quad \text{Eq.08}$$

Solved for k_{NT} we get:

$$F_T(t) = b_T \left[\frac{C_{0NT} + C_{0T}}{C_{0NT}}\right] e^{-(b_T - 1) k_{NT} t}\, F_{NT}(t) \qquad \text{Eq.09}$$

which describes the tillage-induced emission as a function of the non tillage emission depending on how much of labile C was available prior to tillage and induced by tillage (C_{0NT} and C_{0T}).

If we define $a_3 = b_T(\frac{C_{0NT} + C_{0T}}{C_{0NT}})$ and $a_4 = (b_T - 1)k_{NT} = k_T - k_{NT}$ we get:

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

Equations 07 and 10 describe the emissions after tillage as function of the no-till emission and time, once a_1 and a_2 parameters (in model 1) and a_3 and a_4 parameters (in model 2) are known for bare soils, where the sole C emission comes from microbial activity alone.

To summarize (Table 1), parameter a_1 ($C_{0T}k_T$) represents the additional labile C induced by tillage (C_{0T}) and the decay constant in this induced labile C (k_T), while a_2 is the decay constant in the tilled plot (k_T). Parameter a_3, in model 2, also defines 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). However, parameter a4 describes the difference between decay constants k_T of the tilled and non-tilled plot. Our approach of fitting models to data is similar to that used by Wieder & Lang (1982) who discussed a variety of mathematical models for describing decomposition from litter bags.

Data acquisition

The models were applied to data obtained from an experiment conducted in 2002 in Jaboticabal, São Paulo State, Brazil (21°15’22" S, 48°18’58" W), on a Typic Eutrustox, having an organic carbon content close to 11 g kg^{-1} and pH close to 5. The experiment was initiated on 24th July 2002 on a bare soil, where 5 plots were established, each having a single treatment: i) rotary tiller with rotor rotation at 122 rpm, rear shield up (R122-U); ii) rotary tiller at 156 rpm, rear shield up (R156-U); iii) rotary tiller at 156 rpm, rear shield down (R156-D); iv) rotary tiller at 216 rpm, rear shield down (R216-D). The fifth treatment was a control non-disturbed plot that was left unaltered (NT). All the tilled treatments had a 20 cm operation depth. The following hypotheses were tested: i) tillage operation promotes the availability of additional labile carbon (C) to the soil organisms and ii) tillage speed determines the amount C accessible to microorganisms through the break down of protected soil aggregates.

Soil CO_2 emissions were registered with a portable LI-COR chamber (LI-6400, LI-COR, NE, USA). In each of the treatments plots eight replication points (PVC collars) were installed and emissions followed from 24 hours up to 26 days after tillage. No rainfall occurred on the site during the experimental period. A more detailed description of site, tillage and measurement methods can be found in La Scala et al. (2005).

Data analyses

Statistica software (STATSOFT, Inc. 2001) was used to estimate parameters for models 1 and 2 based on the observed data using a non-linear Gauss-Newton approach with a convergence criterion of 10^{-8}.

The applicability of the models to the soil C-CO_2 emission data after tillage was performed by the linear regression between predicted and observed data, by root mean square deviation (RMSD), coefficient of determination (R^2) and index of agreement (d-index). The index of agreement d was calculated by the following expression:

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

where F_t^{obs} is the observed emission value at time t after tillage, having a mean observed emission of $\overline{F}^{obs}$ throughout experiment, and F_t^{pred} is predicted by model emission at a given time t after tillage (Willmott, 1981; Mayer & Butler, 1993; Legates & McCabe, 1999). The d-index values can vary between 0 and 1, being equal to 1 when perfect agreement is found between observed and predicted values (Willmott, 1981).

The R^2 expression used was calculated according to the following expression:

$$R^2 = 1 - \frac{\sum_{t=1}^{n} (F_t^{obs} - F_t^{pred})^2}{\sum_{t=1}^{n} (F_t^{obs} - \overline{F}^{obs})^2}$$

where F_t^{obs}, $\overline{F}^{obs}$ and F_t^{pred} have the same meaning as described above. The expression above is also known as model efficiency with values closer to 1 indicating better model performance (Mayer & Butler, 1993; Legates & McCabe, 1999). The RMSD value was calculated by using the following expression:

$$RMSD = \sqrt{\frac{\sum_{t=1}^{n} (F_t^{obs} - F_t^{pred})^2}{9}}$$

the factor 9 is the degree of freedom in our case (11 observations minus 2 estimated parameters in each model).

Predicted and observed cumulative emissions were also compared based on fitting models 1 and 2 to the observed data. Cumulative emissions were calculated as the integral over time using the area below the emission curves versus time after tillage.

RESULTS AND DISCUSSION

Observed and predicted values of soil C-CO_2 indicate that predicted emissions in the tilled plots showed fluctuations similar to NT emission (Figure 2), suggesting that tillage-induced emissions simulate fluctua-

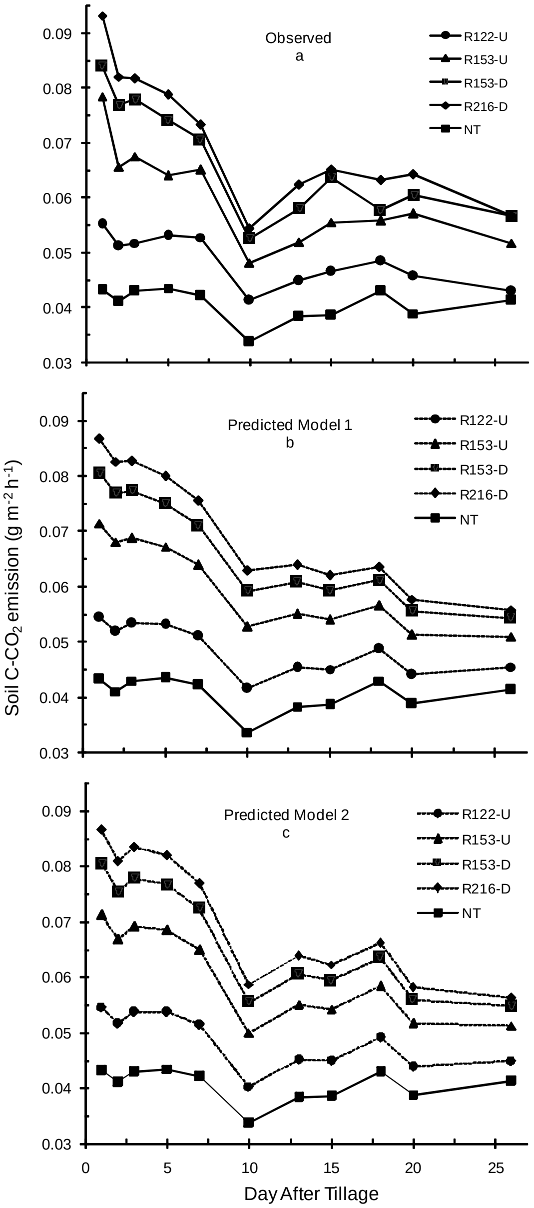

Figure 2 - Observed soil C-CO_2 emission after tillage (2a, solid lines), predicted by model 1 (2b, dashed lines) and predicted by model 2 (2c, dashed lines). No-till curve is inserted in all graphs as a baseline for comparison.

tions due to the changes in soil temperature and moisture of the NT treatment for both models, at least for the short-term. Overall, especially during the first two weeks after tillage, model 2 represented better the minor fluctuations of observed data when compared to model 1. For instance, the sharp decline of emissions between days 1 to 10, and the subsequent increase from days 10 to 15 (Figure 2a) are more accurately described by model 2 than by model 1.

Model 2, in which both labile carbon pools are present, available prior to tillage and made available by tillage, has the same decay factors. Nevertheless, we expect that model 1 may be better applied if a tillage event would introduce a large amount of labile C having a different decay constant, e.g. the incorporation of a fresh crop residue, when compared to previously available labile C. A similar idea was suggested by Ellert & Janzen (1999) in describing the differences between no-till emission and emissions after tillage by using an exponential decay function, similar to our model 1. Different from models derived from empirical approaches, our physical model is based on two main observations reported in the literature: breaking of aggregates making additional labile C available to microbial activity, and a change in the decay constant after tillage.

The R^2 and d-indexes (Tables 2 and 3) and the similarities of the curves shown in Figure 2 indicate model 2 provides better adjustments than model 1. In this experiment changes in soil C-CO_2 emissions over time were first related to soil temperature (La Scala et al., 2005). However, results revealed lower R^2 (0.53 to 0.76) than in the present approach of modeling soil C-CO_2 emission by using equations 07 (model 1) and 10 (model 2) (Tables 2 and 3, respectively). The best R^2 was observed for the rotary tiller speed of 122 rpm and rear shield up (R122-U) treatment with a value of 0.91 and the worst fit was found for the rotary speed of 153 rpm, rear shield up (R153-U), with values of 0.83 and 0.84 for models 1 and 2, respectively. The R^2 values indicate model 2 performs better than model 1. The d-indexes were close to 1, suggesting a high accuracy of both models. However, model 2 had slightly better RMSD values indicating a better adjustment to this model.

Despite model 2 performed only slightly better than model 1 in fitting the data, we believe that it is important to discuss the estimated a_1 and a_2 parameters since they may have important physical interpretations. The a_1 values derived from this experiment ranged from 1.17×10^{-2} to 4.54×10^{-2} g C-CO_2 m^{-2} h^{-1}, while a_2 ranged from 3.98×10^{-2} to 4.40×10^{-2} day^{-1} from R122-U to R216-D, respectively (Table 2). Model 1 indicates that labile C loss induced by tillage had a half life time ($t_{1/2}$) equal to the tilled plot. Therefore, estimated $t_{1/2}$ would range from 17.4 to 15.8 days for R122-U and R216-D, respectively. Those values are much shorter than the half life time reported for crop residues in temperate climates obtained from annual studies (Bayer et al., 2006).

The amount of aggregate protected C becoming unprotected after tillage and, thus, available for microbial decomposition ($C_{0T} = \frac{a_1}{a_2}$) ranged from 0.29 to 1.03 g C m^{-2} for R122-U to R216-D, indicating that with higher rotor rotation speed increases the amount of labile C in soil and decreases the half-life time. Increasing a_1 and a_2 values is also directly related to the increase in cumulative emissions for each level of tillage intensity (Table 2).

Model 2 parameter a_3 ranged from 1.27 to 2.03 (non-dimensional, Table 3). Jacinthe & Lal (2005) found no differences in protected C after chisel and moldboard tillage comparing among tillage intensities. However, our results indicate changes in a_3 (and a_1) when comparing different tillage intensities. According-

Table 2 - Estimated parameters ± standard error, RMSD, R^2, d-index and cumulative emission (observed and predicted) after application of model 1 to experimental data.

Treatment	Model 1	R^2	d-index	RMSD	Cumulative Emission (g C-CO_2 m^{-2})	
	$F_T = F_{NT} + a_1 e^{-a_2 t}$				Observed	Predicted
R122-U	$a_1 = 1.17 \times 10^{-2} \pm 9.02 \times 10^{-4}$					
	$a_2 = 3.98 \times 10^{-2} \pm 8.29 \times 10^{-3}$	0.91	0.977	1.42×10^{-3}	28.25	28.21
R153-U	$a_1 = 2.94 \times 10^{-2} \pm 2.52 \times 10^{-3}$					
	$a_2 = 4.30 \times 10^{-2} \pm 9.52 \times 10^{-3}$	0.83	0.948	3.92×10^{-3}	34.34	34.30
R153-D	$a_1 = 3.90 \times 10^{-2} \pm 2.40 \times 10^{-3}$					
	$a_2 = 4.22 \times 10^{-2} \pm 6.79 \times 10^{-3}$	0.87	0.968	3.74×10^{-3}	37.81	37.79
R216-D	$a_1 = 4.54 \times 10^{-2} \pm 2.87 \times 10^{-3}$					
	$a_2 = 4.40 \times 10^{-2} \pm 7.09 \times 10^{-3}$	0.88	0.967	4.45×10^{-3}	39.74	39.78

$[a_1]$ = g C-CO_2 m^{-2} h^{-1}. $[a_2]$ = day^{-1}. All the parameters significant at $p < 0.01$. [RMSD] = g C-CO_2 m^{-2} h^{-1}.

Table 3 - Estimated parameters ± standard error, RMSD, R², d-index and cumulative emission (observed and predicted) after application of model 2 to experimental data.

Treatment	Model 1	R^2	d-index	RMSD	Cumulative Emission (g C-CO_2 m^{-2})	
	$F_T = a_3 F_{NT}\, e^{-a_4 t}$				Observed	Predicted
R122-U	$a_3 = 1.27 \pm 1.82 \times 10^{-2}$					
	$a_4 = 5.98 \times 10^{-3} \pm 1.14 \times 10^{-3}$	0.91	0.979	1.43×10^{-3}	28.25	28.13
R153-U	$a_3 = 1.67 \pm 4.97 \times 10^{-2}$					
	$a_4 = 1.13 \times 10^{-2} \pm 2.50 \times 10^{-3}$	0.84	0.953	3.80×10^{-3}	34.34	34.38
R153-D	$a_3 = 1.89 \pm 4.74 \times 10^{-2}$					
	$a_4 = 1.36 \times 10^{-2} \pm 2.15 \times 10^{-3}$	0.90	0.972	3.58×10^{-3}	37.81	37.83
R216-D	$a_3 = 2.03 \pm 5.40 \times 10^{-2}$					
	$a_4 = 1.54 \times 10^{-2} \pm 2.31 \times 10^{-3}$	0.90	0.973	4.04×10^{-3}	39.74	39.86

$[a_3]$ = non-dimensional. $[a_4]$ = day^{-1}. All the parameters significant at $p < 0.01$. [RMSD] = g C-CO_2 m^{-2} h^{-1}.

ing to our models, those parameters are related to the amount of labile carbon freed from aggregates by tillage. A similar effect is observed for a_4, which ranged from 5.98×10^{-3} to 1.54×10^{-2} day^{-1}, and increases with the increase of rotor rotation. Treatments that resulted in lower total emissions had smaller a_3 and a_4 parameters and also suggests that the decay constant after tillage (k_T) was higher than under no-till (k_{NT}), since $a_4 = k_T - k_{NT}$. 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 throughout years (Bayer et al., 2006). On an annual basis, we would expect the decay constants for tilled plots to be higher than the non-tilled condition due to increased aeration and soil residue mixing. However, predicting the decay constant maybe a more complex task especially immediately after tillage, due to the short-term changes in soil moisture and temperature (Stevenson & Cole, 1999) as well as complex soil movement during tillage (Spokas et al., 2007).

Another indication of applicability of models is presented in Tables 2 and 3 when cumulative observed and predicted emissions are compared. The highest precision was obtained for R153-D treatment. A deviation of 0.02 g C-CO_2 m^{-2} represents a 0.05% error compared to the observed cumulative emission of 37.81 g C-CO_2 m^{-2} at the end of the 26 day study. This illustrates another potential application of our model for the prediction of short-term cumulative emission after tillage, given parameters are appropriate for the tillage systems and environmental conditions.

CONCLUSIONS

The use of two first-order decay models to describe short-term soil C-CO_2 after rotary tillage indicate that model 2 (single decay constant) performed better when compared to model 1 (different decay constants). Using a non-linear function that takes into account the non-tilled emission as a reference, it was possible to predict the emissions from tilled plots better than using a linear regression with soil temperature. It is expected that each tillage implement will have a range of values for the parameters (for a given set of environmental conditions), therefore making the model a powerful decision tool for the prediction of soil CO_2 emission following tillage. Limitations are related to the fact that model parameters are site, tillage and environmental specific and validation should be made after testing our conceptual functions in several experiments performed in different conditions.

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