## CONTENTS

### AGRICULTURAL ENGINEERING

573-582 Intelligent instrument to facilitate decision making in the evaluation of soil resistance to root penetration  
**Instrumentação inteligente para auxílio à tomada de decisão na avaliação da resistência do solo à penetração de raízes**  
Ladislau Marcelino Rabello; Paulo Estevão Cruvinel

583-592 Antifungal compound produced by the cassava endophyte *Bacillus pumilus MAIIM-4a*  
**Composto antifúngico produzido pelo endófito de mandioca Bacillus pumilus MAIIM-4a**  
Flávia Mandolesi Pereira de Melo; Marlí Fátima Fiore; Luiz Alberto Beraldo de Moraes; Maria Estela Silva-Stenico; Shirley Scramin; Manoel de Araújo Teixeira; Itamar Soares de Melo

### AGRICULTURAL MICROBIOLOGY

593-605 Climate changes and technological advances: impacts on sugarcane productivity in tropical Southern Brazil  
**Mudanças climáticas e avanço tecnológico: impactos na produtividade da cana-de-açúcar na região centro-sul do Brasil**  
Júlia Ribeiro Ferreira Gouvêa; Paulo Cesar Sentelhas; Samuel Thomazella Gazzola; Marcelo Cabral Santos

### AGROMETEOROLOGY

606-614 Economic analysis of soilless and soil-based greenhouse cucumber production in Turkey  
**Estudo econômico da produção de pepino em cultivos com e sem solo em casas de vegetação na Turquia**  
Sait Engindeniz; Ayse Gül

615-621 Economic evaluation of cereal cropping systems under semiarid conditions: minimum input, organic and conventional  
** Avaliação econômica de sistemas de cultivo de cereais em condições semiáridas: cultivo mínimo, orgânico e convencional**  
Gabriel Pardo; Joaquin Aibar; José Cavero; Carlos Zaragoza

### APPLIED ECONOMY

622-628 Physiological model to estimate the maturity of sugarcane  
**Modelo fisiológico para a estimativa da maturação em cana-de-açúcar**  
Maximiliano Salles Scarpelli; Edgar Gomes Ferreira de Beauclair

### FOOD SCIENCE AND TECHNOLOGY

629-633 Enriching nutritive value of cassava root by yeast fermentation  
**Enriquecimento do valor nutritivo da mandioca por fermentação com leveduras**  
Krisada Boonnop; Metha Wanapat; Ngarmnit Nontaso; Sadudee Wanapat

### PLANT PHYSIOLOGY AND BIOCHEMISTRY

634-642 Extraction, partial characterization and susceptibility to Hg^{2+} of acid phosphatase from the microalgae *Pseudokirchneriella subcapitata*  
**Extracção, caracterização parcial e susceptibilidade ao Hg^{2+} da fosfatase ácida da microalga Pseudokirchneriella subcapitata**  
Cláudio Martín Jonsson; Hiroshi Aoyama

### SOILS AND PLANT NUTRITION

643-649 Heavy metals extractability in a soil amended with sewage sludge  
**Extractabilidade de metais pesados em um solo tratado com lodo de esgoto**  
Giuliano Marchi; Luiz Roberto Guimarães Guilherme; Andrew C. Chang; Clistenes Williams Araújo do Nascimento

650-657 First-order decay models to describe soil C-CO₂ loss after rotary tillage  
**Modelos de decaimento de primeira ordem aplicado a descrição da perda de C-CO₂ do solo após preparo com enxada rotativa**  
Newton La Scala Jr.; Afonso Lopes; Kurt Spokas; David Walter Archer; Donald Reicosky

658-666 Soil erosion fragility assessment using an impact model and geographic information system  
** Avaliação da fragilidade à erosão do solo por meio de um modelo de impacto e sistema de informações geográficas**  
Luiz Alberto Blanco Jorge

667-676 Sesbania virgata stimulates the occurrence of its microsymbiont in soils but does not inhibit microsymbionts of other species  
* Sesbania virgata estimula a ocorrência de seu microsímbionte nos solos, mas não inibe os microsímbiontes de outras espécies  
Ligiane Aparecida Florentino; Ana Paula Guimarães; Márcia Ruffini; Krisle de Silva; Fátima Maria de Souza Moreira

677-684 Arbuscular mycorrhizal fungal communities in native and in replanted *Araucaria* forest  
**Comunidades de fungos micorrízicos arbusculares em floresta nativa e replantada de araucária**  
Milene Moreira; Dilmar Baretta; Sin Mui Tsoi; Elke Jurandy Bran Nogueira Cardoso
Microsatellite markers for identification of a group of Italian olive accessions

Identiicação de grupos de cultivares italianos de oliva com marcadores microsatélites

Innocenzo Muzzalupo; Francesca Stefanizzi; Amelia Salimonti; Rosanna Falabella; Enzo Perri

Microsporogenesis in Brachiaria bovonei (Chiov.) Robyns and B. subulifolia (Mez) Clayton (Poaceae)

Microsporogênese em Brachiaria bovonei (Chiov.) Robyns e B. subulifolia (Mez) Clayton (Poaceae)

Claudicéia Risso-Pascotto; Maria Suely Pagliarini; Cacilda Borges do Valle
INDEX OF AUTHORS

Aibar, J., 615
Aoyama, H., 634
Archer, D.W., 650
Baretta, D., 677
Beauclair, E.G.F., 622
Boonnop, K., 629
Buol, S.W., 697
Cardoso, E.J.B.N., 677
Cavero, J., 615
Chang, A.C., 643
Cruvinel, P.E., 573
Engindeniz, S., 606
Falabella, R., 685
Fiore, M.F., 583
Florentino, L.A., 667
Gazzola, S.T., 593
Gouvêa, J.R.F., 593
Guilherme, L.R.G., 643
Guimarães, A.P., 667
Güll, A., 606
Jonsson, C.M., 634
Jorge, L.A.B., 658
La Scala Jr., N., 650
Lopes, A., 650
Marchi, G., 643
Melo, F.M.P., 583
Melo, I.S., 583
Moraes, L.A.B., 583

Moreira, F.M.S., 667
Moreira, M., 677
Muzzalupo, I., 685
Nascimento, C.W.A., 643
Nontaso, N., 629
Pagliariini, M.S., 691
Pardo, G., 615
Perri, E., 685
Rabello, L.M., 573
Reicosky, D., 650
Risso-Pascotto, C., 691
Rufini, M., 667
Salimonti, A., 685
Santos, M.C., 593
Scarpari, M.S., 622
Scramin, S., 583
Sentelhas, P.C., 593
Silva, K., 667
Silva-Stenico, M.E., 583
Spokas, K., 650
Stefanizzi, F., 685
Teixeira, M.A., 583
Tsai, S.M., 677
Valle, C.B., 691
Wanapat, M., 629
Wanapat, S., 629
Zaragoza, C., 615
ABSTRACT: To further understand the impact of tillage on CO₂ emission, the applicability of two conceptual models was tested, which describe the CO₂ 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: \( \frac{dC_{\text{soil}}(t)}{dt} = -k C_{\text{soil}}(t) \), and that soil C-CO₂ emission is proportional to the C decay rate in soil, where \( C_{\text{soil}}(t) \) 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 (Fₜ) 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 (Fₙ) and tilled (Fₜ) conditions are given by: \( F_T = F_{NT} + a_1 e^{-a_2t} \) (model 1) and \( F_T = a_3 F_{NT} e^{-a_4t} \) (model 2), where t is time after tillage. Predicted and observed CO₂ 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
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: $F_{NT} \frac{dC_{NT}}{dt}$ 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:

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

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:

$$C_{soil}(t) = C_0 e^{kt}$$

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
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:

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

The higher the decay rate, the higher the soil C-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:

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

These relationships are presented as proportionality 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-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.

$$F(t) = C_0 ke^{-kt}$$

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:

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

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:

$$C_{\text{soil}}(t) = C_{NT}(t) + C_{T}(t) \quad \text{Eq.05}$$

As supposed for the tillage plot, C-CO$_2$ emission comes from the soil labile organic matter oxidation given by:

$$F_t(t) = -\frac{dC_{\text{soil}}}{dt} = -\frac{d}{dt}(C_{NT} + C_{T}) = -\frac{dC_{NT}}{dt} - \frac{dC_{T}}{dt} \quad \text{Eq.06}$$

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-CO$_2$ flux from tilled plot should be derived by:

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

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:

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

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-CO$_2$ flux would be given by:

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

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

$$F_T(t) = C_{0NT} k_T e^{k_T t} + C_{0T} k_T e^{k_T t} \quad \text{Eq.05}$$

Sci. Agric. (Piracicaba, Braz.), v.66, n.5, p.650-657, September/October 2009
Multiplying and dividing by the non-tilled C-CO\textsubscript{2} flux, we have:

\[ F_t(t) = \frac{C_{ONT}k_T e^{\kappa_{NT}t} + C_{OT}k_T e^{\kappa_{OT}t}}{C_{ONT}k_N} e^{\kappa_{NT}t} \]

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:

\[ F_t(t) = \frac{C_{ONT}b_T k_{NT} e^{\kappa_{NT}t} + C_{OT}k_T e^{\kappa_{OT}t}}{C_{ONT}k_{NT} e^{\kappa_{NT}t}} F_{NT}(t) \]

Solved for \( k_{NT} \) we get:

\[ F_t(t) = b_T \left( \frac{C_{ONT} + C_{OT}}{C_{ONT}} \right) e^{(b_T - 1)k_{NT}t} F_{NT}(t) \]

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 (\( C_{ONT} \) and \( C_{OT} \)).

If we define \( a_3 = b_T \left( \frac{C_{ONT} + C_{OT}}{C_{ONT}} \right) \) and \( a_4 = (b_T - 1)k_{NT} \),

\[ k_T - k_{NT} \]

we get:

\[ F_t = a_3 F_{NT} e^{a_4t} \]  (Model 2)  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 \( a_1 \) \( (C_{ONT}k_T) \) represents the additional labile C induced by tillage (\( C_{OT} \)) 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 (\( C_{ONT} + C_{OT} \)) and how the decay constant was altered by the tillage event (\( b_T \)). However, parameter \( a_4 \) 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°15’12” S, 48°18’58” W), on a Typic Eutrustox, having an organic carbon content close to 11 g kg\textsuperscript{-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 follow-


ing 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 CO₂ 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-CO₂ emission data after tillage was performed by the linear regression between predicted and observed data, by root mean square deviation (RMSD), coefficient of determination (R²) and index of agreement (d-index). The index of agreement d was calculated by the following expression:

\[
d = 1 - \frac{\sum_{t=1}^{n} (F_{t}^{\text{obs}} - F_{t}^{\text{pred}})^2}{\sum_{t=1}^{n} (|F_{t}^{\text{obs}}| + |F_{t}^{\text{pred}}|)^2}
\]

where \(F_{t}^{\text{obs}}\) is the observed emission value at time t after tillage, having a mean observed emission of \(F^{\text{obs}}\) throughout experiment, and \(F_{t}^{\text{pred}}\) 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 R² expression used was calculated according to the following expression:

\[
R^2 = 1 - \frac{\sum_{t=1}^{n} (F_{t}^{\text{obs}} - F_{t}^{\text{pred}})^2}{\sum_{t=1}^{n} (F_{t}^{\text{obs}} - F^{\text{obs}})^2}
\]

where \(F_{t}^{\text{obs}}, F^{\text{obs}}\) and \(F_{t}^{\text{pred}}\) 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:

\[
\text{RMSD} = \sqrt{\frac{\sum_{t=1}^{n} (F_{t}^{\text{obs}} - F_{t}^{\text{pred}})^2}{9}}
\]

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-CO₂ 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](image-url)
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 R² 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-CO₂ emissions over time were first related to soil temperature (La Scala et al., 2005). However, results revealed lower R² (0.53 to 0.76) than in the present approach of modeling soil C-CO₂ emission by using equations 07 (model 1) and 10 (model 2) (Tables 2 and 3, respectively). The best R² 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 R² 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 a₁ and a₂ parameters since they may have important physical interpretations. The a₁ values derived from this experiment ranged from 1.17 × 10⁻² to 4.54 × 10⁻² g C-CO₂ m⁻² h⁻¹, while a₂ 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 (t₁/₂) equal to the tilled plot. Therefore, estimated t₁/₂ 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 (C₀T = a₁/a₂) 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 a₁ and a₂ values is also directly related to the increase in cumulative emissions for each level of tillage intensity (Table 2).

Model 2 parameter a₁ 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 a₁ (and a₂) when comparing different tillage intensities. According to this study, model 2 provided a better fit compared to model 1. The results of model 2, which accounts for the incorporation of labile C pools, were more consistent with the observed data. Therefore, we suggest using model 2 to accurately describe soil C-CO₂ emissions over time.
The use of two first-order decay models to describe short-term soil C-CO\(_2\) after rotary tillage indicated 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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