

Simulation of Soil CO₂ Flux During Plant Residue Decomposition

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Abstract: Based on information obtained from recent studies, we modified the CENTURY model to improve simulation of short-term soil respiration, especially in soils with surface-applied crop residues. This involved adding N availability as a factor controlling the decomposition rate. Translocation by filamentous fungi was assumed to be the mechanism supplying mineral N to residues decomposing on the soil surface. When available N is non-limiting, the N availability factor is 1, otherwise decomposition rates of all pools of soil surface and below-ground organic matter are reduced proportionately until N supply meets demand. The modified model was evaluated using CO₂ flux data from a laboratory experiment which included different wheat (*Triticum aestivum* L.) straw types (fresh and weathered straw), straw placements (incorporated and surface-applied) and soil water regimes (continuously moist and alternating moist-dry conditions). In general, CENTURY successfully simulated daily CO₂ fluxes in these treatments, except for an underestimation in the first day after watering and an overestimation immediately after re-wetting dry soil in the moist-dry water regime. For treatments with surface-applied straw, CENTURY overestimated soil respiration, while the modified version gave substantially better simulations. The correlation between measured and simulated total (in 77 d) respiration was improved by model modification. CENTURY underestimated the soil mineral N remaining in the soil at the end of the experiment. The modified model gave improved mineral N simulations for the surface straw treatments.

1 Introduction

The concentration of CO₂ in the atmosphere has increased substantially since the beginning of the industrial revolution. There are concerns that continuing increases in levels of CO₂ and other greenhouse gases will contribute to climate change. Soils contain about three times as much C as the atmosphere, and they have the potential to store additional C (Campbell and Zentner, 1993). Research shows that, if properly managed, agricultural lands could be an important sink for C (Janzen *et al.*, 1998). Reduction in tillage intensity, especially the adoption of no-tillage (NT) cropping, is widely recognized as an effective management technique to enhance C storage in soil (Kern and Johnson, 1993; Lal and Kimble, 1997; Dao, 1998). Many long-term experiments have shown that adoption of NT may increase soil organic matter (SOM) in temperate regions and sub-humid and humid tropics (Paustian *et al.*, 1997a). The effect of management on C sequestration is strongly affected by weather, soil conditions (e.g., texture) and agronomic factors, such as crop rotation, fertilizer application and residue treatment (Janzen *et al.*, 1998). As a result, the SOM gain in response to NT can vary widely within a region such as the Canadian prairies (Campbell *et al.*, 1995, 1996; Janzen, *et al.*, 1998).

Given the complexity and multifaceted interactions between the factors listed above, simulation models that describe soil organic matter turnover and N dynamics in soils are useful for estimating management-induced SOM changes (Paustian *et al.*, 1997b). The CENTURY model (Parton *et al.*, 1987) is one such model. It was originally developed for simulating long-term management effects on SOM in Great Plains grasslands. It is widely used, and it has been extensively evaluated, in a variety of ecosystems and locations (Paustian *et al.*, 1992; Kelly *et al.*, 1997; Scholes *et al.*, 1997; Smith *et al.*, 1997). Recently, CENTURY has been used to simulate short-term changes in soil organic matter. Del

Grosso *et al.* (2001) used the DAYCENT model (Parton *et al.*, 1998), which is the daily time step version of CENTURY, to simulate daily C dynamics and trace gas fluxes. The System Approach to Land Use Sustainability program (SALUS), which combines a daily-based crop growth model and CENTURY, was developed to simulate continuous crop, soil, water and nutrient conditions under different managements (Schulthess and Ritchie, 1996). Paul *et al.* (1999) used SALUS to predict the intra- and inter-year differences in field CO₂ fluxes. Recently, the CENTURY SOM module was incorporated into the Decision Support System for Agrotechnology Transfer software program (DSSAT) and this improved simulations of residue decomposition (Gijsman and Bowen, 1999; Gijsman, 2000).

Because crop residues have a short turnover time in soil compared with other SOM pools (Parton *et al.*, 1987), their decomposition strongly affects the short-term dynamics of soil C. Curtin *et al.* (2000) indicated that the lower CO₂ flux under NT than under conventional tillage could be attributed to slower decomposition of crop residues on the surface of NT soil than when they were incorporated by tillage. Duiker and Lal (2000) concluded that lack of significant difference in soil CO₂ flux between treatments receiving different rates of surface-applied residue was partly due to undecomposed surface residue which did not contribute to the CO₂ flux. Although CENTURY contains above- and below-ground C pools, decomposition of above-ground pools is not well-described because quantitative studies on the mechanism of soil surface decomposition are limited (Frey *et al.*, 2000). The objective of this study was to use information provided by recent research to modify the CENTURY model in order to improve the simulation of short-term soil CO₂ emissions, especially when plant residue is applied on the soil surface.

2 Materials and methods

Details of this laboratory experiment have been reported by Curtin *et al.* (1998).

The CENTURY model and modification

CENTURY (Parton *et al.*, 1987) is a computer simulation model of plant-soil ecosystems that simulates the dynamics of grasslands, forest and crops. The grassland, crop and forest systems have different growth submodels which are linked to a SOM submodel that includes three soil organic matter pools (active, slow and passive), above- and below-ground plant residue pools, and a surface microbial pool. The active pool represents microbes and microbial products and it has a turnover time of 1yr—5 yr. The slow pool includes resistant plant material and soil-stabilized microbial products and it has a turnover time of 20 yr to 50 yr. The passive pool includes physically and chemically stabilized SOM with a turnover time of 400 yr to 2000 yr. Above- and below-ground plant residues are partitioned into structural and metabolic pools as a function of the lignin-to-N ratio in the residue. Turnover times for structural and metabolic pools are 1yr —5 yr and 0.1yr —1 yr, respectively. Decomposition of each pool is assumed to be microbially- mediated with an associated microbial respiration. Each pool has a potential decomposition rate which is reduced by multiplicative functions of soil moisture and soil temperature. Each SOM pool has an allowable range for the ratio of C to other elements. Flows of nitrogen and phosphorus between SOM pools are related to the C flows. The quantity of each element flowing out of a particular pool equals the product of the C flow and the C-to-element ratio of the pool. Mineralization or immobilization of N and P occurs as is necessary to maintain the ratios. The decomposition rate is reduced if the quantity of any element is insufficient to meet the immobilization demand. Detailed descriptions of the model are given by Parton *et al.* (1987), Paustian *et al.* (1992) and Metherell *et al.* (1993).

In the CENTURY model, potential decomposition rates of the surface plant residue pools and surface microbial active pool are arbitrarily set at 20% lower than those of in-soil pools, because it is assumed that moisture conditions are less optimal on the surface than in the soil (Parton *et al.*, 1987). However, it is recognized that, in addition to the moisture factor, the availability of N also influences the decomposition rate (Parr and Papendick, 1978; Henriksen and Breland, 1999). It is relatively easy to simulate the N availability for SOM pools because mineral N in the same soil layer should be readily available for use in decomposition. The main N source for decomposing surface C pools is considered to be soil N obtained by fungal translocation (Hendrix *et al.*, 1986; Beare *et al.*, 1992). Recently, Frey *et al.*

(2000) found that the annual N flux by filamentous fungi from the soil to surface-applied wheat straw in a NT field in Colorado was $2.4 \text{ g} \cdot \text{m}^{-2}$. They also showed that the N flux mediated by fungi was constant over the period of their test (185 d after the placement of straw). The N flux would be expected to increase under conditions of high soil N availability (Holland and Coleman, 1987) and low initial residue N concentration (Frey *et al.*, 2000). This information provided an opportunity for us to modify the CENTURY model in order to improve the simulation of soil CO₂ emissions, especially where crop residues are placed on the soil surface, as under NT management.

In addition to soil moisture and soil temperature, we therefore included N availability as a multiplicative factor to reduce potential decomposition rates. We assumed that mineral N present in the soil layer to which residues are incorporated is readily available for use in decomposition, while only the limited amount of N translocated from the soil by fungi will be available for decomposition of surface residues. Further, it was assumed that the N flux rate from soil to the surface residue is constant. Available N was estimated on a daily basis for the soil and soil surface separately. When the available N is sufficient for decomposition of soil or surface pools, the N availability factor is 1, otherwise decomposition rates of all pools of soil surface and below-ground organic matter are reduced proportionately until N supply meets demand. As the initial concentrations of soil mineral N and straw N in the study by Frey *et al.* (2000) were close to those in our experiment (Curtin *et al.*, 1998), we assumed a daily rate of potential N supply from soil to surface straw via fungal translocation of 6.6 mg N m^{-2} (i.e., $2.4 \text{ g} \cdot \text{m}^{-2} \cdot \text{y}^{-1}$).

We used only the SOM submodel of CENTURY (version 4) for simulations of soil CO₂ flux during plant residue decomposition under the controlled conditions. The time step was changed from a weekly to daily basis.

The proportions of SOM in the active, slow and passive pools were assumed to be 3%, 45% and 52%, respectively. Monreal *et al.* (1997) used this pool size allocation as the initial (1967) distribution of organic matter when simulating long-term crop rotation effects on SOM in soils of the Canadian prairies. The simulated changes in soil organic C and N were close to the observed values and they were superior to those achieved using CENTURY in Sweden (Parton *et al.*, 1982) and on the Great Plains (Cole *et al.*, 1989). Effects of soil moisture on decomposition were calculated (using relative water content data) using the equation provided by CENTURY. The temperature effect was calculated by an equation obtained from the CENTURY Tutorial (Parton *et al.*, 2001).

The performances of CENTURY and the modified model were evaluated and compared using the following statistics. The association between simulated daily CO₂-C fluxes and measured values was assessed by Pearson's correlation (r). Systemic errors were determined by the sum of squares attributable to lack of fit (LOFIT) (Whitmore, 1991). This method enables the experimental errors to be distinguished from the failure of the model. The statistical significance of LOFIT was obtained by comparing the ratio between the mean square due to lack of fit and the mean square due to the random error to tabulated F values with the appropriate degrees of freedom (Smith *et al.*, 1996). The mean difference between measurement and simulation (M) was calculated to evaluate consistent errors (Addiscott and Whitmore, 1987). Pearson's correlation was calculated between measured and simulated values of total CO₂-C evolution and soil mineral N at the end of the experiment.

3 Results and discussion

3.1 Daily CO₂ fluxes

The soil had a mineral N content of $18.4 \text{ mg N kg}^{-1}$ soil at the beginning of the experiment. According to CENTURY, decomposition of incorporated straw should not be limited by N availability. Consequently, simulated values of daily CO₂ flux for no-straw controls and treatments with incorporated straw were the same using the modified model as when the original CENTURY model was used.

In the no-straw control under continuously moist conditions (Fig. 1a), small fluctuations of daily CO₂ evolution occurred throughout the experiment. This appeared to be due mainly to day-to-day drift of the equipment (LI-COR LI-6000 analyzer) as the measurement accuracy of the LI-6000 system is about $\pm 10\%$. Towards the end of the experiment, soil respiration increased slightly, possibly due to growth of moulds on the soil surface as a result of the high moisture and humidity. This was also observed for other

continuously moist treatments (Fig. 1b, c, d, and e). For the reasons given above, the correlation between measured and simulated values of daily CO₂ flux was poor in the no-straw (continuously moist) treatment and both systemic errors (LOFIT) and consistent errors (M) were high. However, the simulation line was within, or very close to, the standard error of most of the measured data indicating that the simulated values were reasonably acceptable.

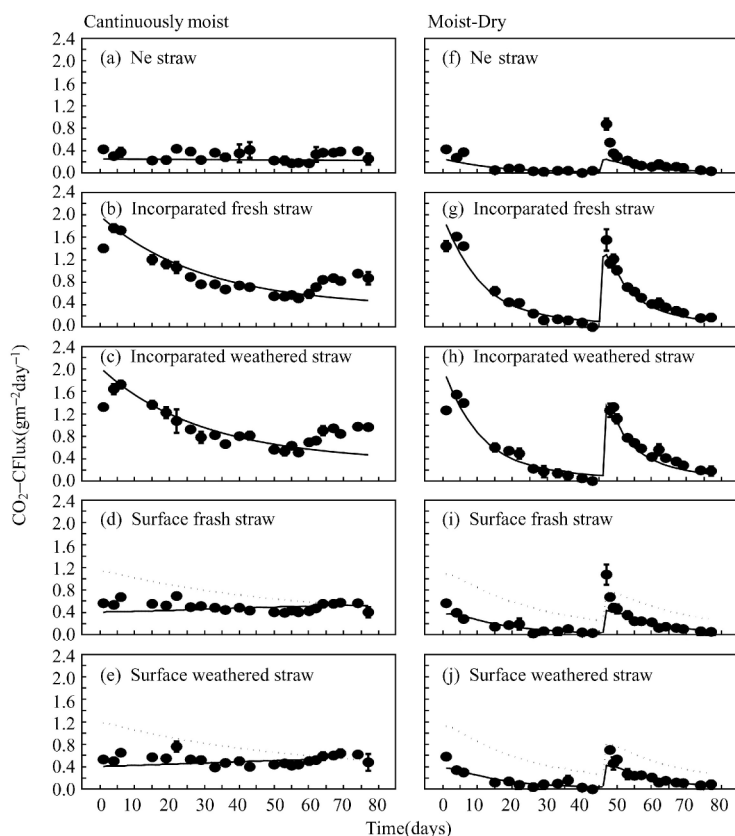


Fig.1 Measured and predicted (CENTURY, -modified model) daily CO₂-C fluxed Bars are standard errors of measurement

The two straw types (fresh and weathered straw) had similar composition [i.e., lignin, cellulose and hemicellulose contents, and C : N ratios (Curtin *et al.*, 1998)]; as a result, CO₂ flux from fresh straw treatments was very similar to that of corresponding weathered straw treatments (Fig. 1). For straws incorporated into continuously moist soil, there were good correlations between simulated and measured CO₂ fluxes, indicating that the pattern of CO₂ production was generally matched by the CENTURY simulation. However, the model tended to overestimate the CO₂ flux one day after the first water application to the incorporated straw treatments (Fig. 1b and c). Paul *et al.* (1999) attributed an overprediction of CO₂ evolution by the SALUS model to the fact that the model does not consider the lag period prior to residues being colonized and comminuted. In our study, predicted CO₂ fluxes were in good agreement with measured values by day four after the first watering, suggesting that colonization occurred rapidly compared with the field situation. This may be because the straw used in our experiment was cut into small (2.5 cm) pieces and it was mixed well into the soil. The overestimation on day one after the first watering and the increases of CO₂ flux before the end of the experiment were main reasons for the significant lack of fit between measured and simulated values. However, the t tests for M indicate that there was no significant bias in the simulations for either straw type.

Under moist-dry conditions, CENTURY successfully simulated the soil respiration pattern of the no-straw control and treatments with incorporated straws (Fig. 1f, g, and h), as shown by highly significant *r*

values. As in the continuously moist environment, the model overestimated the CO₂ flux on day one after the initial watering. Large flushes of CO₂ production were observed immediately after the rewatering, which may be attributed to fast mineralization of labile organic substances (Dao, 1998) and/or release of trapped CO₂ by displacement with water. CENTURY does not take these process into account and it underestimated respiration on the first day (incorporated straw treatments) or two (no-straw control) after rewatering. The *F* tests for LOFIT indicate that the error in the simulated values was significantly greater than the error inherent in the measured values for all three treatments. This was mainly due to the overestimation of respiration after the first watering and underestimation after the second watering. However, as shown by *M* values, the consistent error was only significant for the no-straw control.

In general, CENTURY overestimated CO₂ fluxes from treatments with surface-placed straw (Fig. 1d, e, i, and j). The modified model greatly improved the simulation in these cases. According to calculations using the modified model, decomposition rates of C pools on the soil surface were only about 15%—30% (continuously moist soil) and 13%—20% (moist-dry conditions) of those of the corresponding in-soil pools. These results suggest that N availability may be a serious limitation to the decomposition of surface-placed straw. All statistics used to evaluate the simulations, except the *r* for treatments under the continuously moist conditions, were better for the modified vs the original CENTURY model. Respiration rates simulated by the modified model were relatively constant during the period of the experiment (0.4—0.5 g CO₂-C m⁻² • day⁻¹). In contrast, the original model predicted a significant decline with time in the CO₂ flux. Measured values showed little, if any, trend with time.

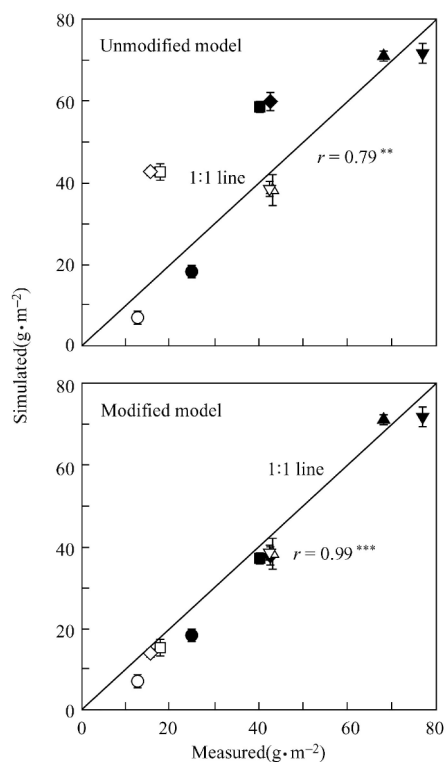


Fig.2 Measured and predicted total CO₂-C emissions (!"no straw controls, ® * fresh straw incorporated, (* weathered straw incorporated, @ ", fresh straw on the surface, ②, ① weathered straw on the surface under continuously moist (closed symbols) and moist-dry (open symbols) conditions. Bars are standard errors of measurements

3.2 Total CO₂ emissions

CENTURY satisfactorily simulated total CO₂-C production during the experimental period for the no-straw controls and the incorporated straw treatments under the two water regimes (Fig. 2). Simulated

values of total respiration in the incorporated straw treatments were within, or very close to, the standard error of the measured values. The model slightly underestimated the total respiration for the two controls. CENTURY overestimated the total respiration for all treatments with straw applied on the soil surface, while the modified model greatly improved the simulation for these treatments. Overall, the correlation between measured and simulated total soil respiration was improved by modification of CENTURY.

3.3 Soil mineral N

CENTURY underestimated soil mineral N remaining at the end of the experiment in all treatments and, especially, in the treatments with straw applied on the soil surface under the moist-dry conditions (Fig. 3). However, the linear relationship between measured and simulated values ($P < 0.001$) suggests that the structure of CENTURY is generally sound, though it could be further improved. The modified model improved simulation for treatments with surface-applied straw and therefore improved the relationship for mineral N (Fig. 3).

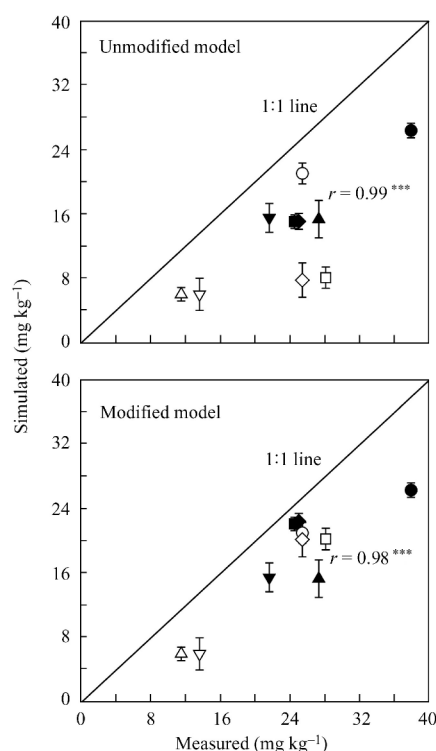


Fig.3 Measured and predicted soil mineral N at the end of the experiment (!",no straw controls,[⊙]* fresh straw incorporated,* weathered straw incorporated,[⊙]", fresh straw on the surface,^{⊙,⊙} weathered straw on the surface under continuously moist(closed symbols) and moist-dry (open symbols) conditions. Bars are standard errors of measurements

4 Conclusions

The CENTURY model appeared to be structurally sound in predicting the trend of soil respiration under different straw managements and soil moisture conditions in a controlled chamber experiment.

Modifications of the model were made to include an N availability factor and this resulted in improved simulations of soil respiration when plant residue was applied on the soil surface. In this study, decomposition of incorporated straw was not limited by N availability. Further studies to quantify the inter-relationships between N availability, surface residue decomposition, and environmental factors are needed in order to improve models of soil C cycling, particularly under no till conditions.

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