Evaluation of the CENTURY Model with Laboratory Measured Soil Respiration

H. Wang, D. Curtin, Y.W. Jame, B. McConkey, and H.F. Zhou

H. Wang, Y.W. Jame, and B. McConkey, Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada, Box 1030, Swift Current, SK S9H 3X2; D. Curtin,New Zealand Institute for Crop & Food Research, Private Bag 4704, Christchurch, New Zealand; and H.F. Zhou, Shenyang Agricultural University, 120 Dongling Road, Shengyang, PRC.

ABSTRACT

The CENTURY model is widely used in assessing the effect of management on soil C dynamics. However, recent testing of the model revealed that it performed unsatisfactorily in simulating soil C changes in southwestern Saskatchewan, suggesting that the model may need further testings and modifications. Evaluations of the model were made with measurements conducted in an laboratory experiment which included different straw placements (incorporated in the soil and applied on the soil surface) and soil water regimes (continuously moist and moist-dry). Results from model testing revealed some weaknesses of the model and modifications were made to improve model performance. The temperature function was modified to slightly increase the relative decomposition rate when temperatures were below the reference temperature. The moisture function was modified to reduce the relative decomposition rate when the soil moisture was very low. The modified model also assumed that soil mineral N is readily available for the use of decomposition of soil C pools, but only about 6.6 mg m^{-2} d^{-1} of soil N is available for C pools on the soil surface. When N availability is less than that required for maximum decomposition rates of soil or surface pools, decomposition rates of these pools were reduced until supply met demand. The modified model improved simulations of daily C fluxes, cumulative CO_2 emissions and soil mineral N. To use this modified model for estimating soil respiration in the field, further studies on the N availability for soil surface C pools and the dryness of surface-placed residue are needed.

The concentration of CO_2 in the atmosphere has increased by about 25% since the beginning of the industrial revolution. There are concerns that continuing increases in levels of CO_2 and other greenhouse gases will contribute to global warming. Soils contains about three times as much C as the atmosphere, and they have the potential to store additional C (Campbell and Zentner, 1993). Agricultural soils on the Canadian prairies contain about 3 Pg soil organic carbon (SOC) in the top 30 cm layer, which is about 20 times the amount of CO_2-C emitted annually by fossil fuel combustion in Canada.

Research shows that if properly managed agricultural lands could be an important sink for C. Management options to enhance C storage in Canadian prairie soils include: decreasing summer fallow frequency, reducing tillage, including legumes in crop rotations, proper fertilization, and growing forage and trees on marginal lands (Campbell and Zentner, 1993; Campbell et al., 1995). For example, reduction in tillage intensity, especially no-tillage (NT) cropping, has been shown to increase SOC at various locations (Janzen, et al. 1998).

Although changes in SOC occur when soil management practices are altered (Mann, 1986), it is common for these changes to remain undetectable for 10 or 20 years. The reason is that because of the inherent spatial variability of SOC in the field, too many samples are required to be taken to ensure that small differences can be statistically separated (Campbell et al., 1976; Campbell et al., 2000). Thus, we often use a process-based simulation model that describes soil organic matter turnover and nitrogen cycling dynamics in soils to estimate management induced SOC changes. The CENTURY model (Parton et al., 1987) is one of such models that is the most widely used and has been extensively evaluated in various ecosystems (Scholes et al., 1997). However, the recent testing of the CENTURY model revealed that it performed unsatisfactorily in simulating soil C changes in a 30-yr crop rotation experiment in southwestern Saskatchewan (Campbell et al., 1999), suggesting that the model may need further testings and modifications for use on the Canadian prairies.

Because of the problems associated with SOC measurement and the variability of environmental conditions in the field, it is difficult to rigorously test the mechanism of a process-based soil organic matter model. Alternatively, the model can be readily tested against measurements of CO_2 emissions from a controlled laboratory experiment. The objectives of this study were thus: (1) to test the validity of the CENTURY model with the soil respiration measured from laboratory experiments and (2) to address the weaknesses revealed during the model testings by modifying the model.

MATERIALS AND METHODS

Experiment

Details of this laboratory experiment have been reported by Curtin et al. (1998). It was conducted in an environment-controlled growth chamber with the air temperature of 20^{o}C and relative humidity of 60%. Samples of Swinton silt loam (Typic Haploboroll; C and N contents of 15 and 1.5 g kg^{-1}) were placed into wooden boxes (39.5 by 34.5 by 10 cm) lined with black polythene sheets and packed to a bulk density of 1.0 Mg m^{-3}.

Treatments consisted of two straw types, two different straw placements and two soil moisture regimes plus a no straw check for each water regime. The two types of straw were "fresh" straw from the 1994 crop and "weathered" straw from the 1993 crop. The weathered straw consisted of standing stubble on plots that had been fallowed in 1994 without any tillage but with weeds controlled by herbicides as required. Both straw types, which were from the same variety (cv. Lancer), were collected in November, 1994. Wheat straw was applied at a rate of 38.2 g per box (equivalent to 2800 kg ha^{-1}). As the "fresh" straw was collected three months after harvest, it was actually also more or less "weathered" in the field and there was little difference in C/N ratio, lignin content or CO_2 emission between the two straw types (Curtin, et al., 1998). Therefore, only results from experiments with "weathered" straw were used for the model testing.

Straw placement treatments included straw applied on the soil surface (designated as S) or incorporated uniformly into the soil (designated as I). In the two moisture treatments, soils were either watered every 2 or 3 days to 90% of field capacity (designated as W) or allowed to dry from field capacity to below permanent wilting point before addition of water (designated as

D). treatments with no straw applied were designated as N. Thus, the six treatments reported in this paper are:

IW : straw incorporated with continuously moist soil
SW: surface straw with continuously moist soil
NW: no straw with continuously moist soil
ID : straw incorporated with moist-dry soil
SD: surface straw with moist-dry soil
ND: no straw with moist-dry soil

There were three replications for each treatment.

Emissions of CO_2 were measured every two or three days using a portable infrared analyzer (LI-COR Model LI-6000, LI-COR inc., Lincoln, NE) during the 77d experiment. Before the end of the experiment, soil respirations from continuously moist treatments increased slightly (Curtin et al., 1998), which could be caused by the development of molds on the soil surface because of the high moisture and relative humidity (60%). To remove uncertainty, simulations were run only up to 57 days for wet treatments. The experiment results also showed a large release of CO_2 right after the rewatering of dry treatments (Curtin et al., 1998). It was considered unlikely that these high fluxes were a direct result of organic matter decomposition and they were tentatively attributed to the release of trapped CO_2, a process not simulated by the CENTURY model. Therefore, the measurements made on the day of rewatering (day 47) were not included in the analysis. Total CO_2 production during the period of experiment was calculated by linear interpolation of the mean fluxes and integration over time. Original and recovered straw at the end of the experiment was analysed for lignin, total N and C. As well, soil mineral N was determined at the beginning and the end of the experiment.

The Model

The CENTURY model (Parton et al., 1987) is a computer model of plant-soil ecosystems which simulates the dynamics of grasslands, forest and crops. The carbon submodel simulates the dynamics of C in the organic and inorganic parts of the soil system. Detailed descriptions of the model are given by Parton et al. (1987), Paustian et al. (1992) and Metherell et al. (1993). The source code of CENTURY model (version 4) used in this study was downloaded directly from the website (http://www.nrel.colostate.edu/ PROGRAMS/MODELING/CENTURY/CENTURY.html). We used only submodels directly related to the decomposition of plant residues and soil organic matter and N transformation in soil for model testing. The time step for the calculation of decomposition was changed from weekly to daily.

In the CENTURY model, total SOC is divided into active, slow and passive soil C fractions. Metherell et al. (1993) indicated that the active SOC pool is about 2 to 3 times the size of the live microbial biomass. Average microbial biomass C for 0-15cm depth soil in the experimental farm (fallow phase of conventional fallow-wheat rotation) was 1.6% of the total soil C (unpublished data, 1976). In an experiment conducted at IACR Rothamsted, UK, unfertilized soil, annually fertilized with inorganic or organic fertilizer soils had the same portion of microbial biomass C in the total soil C (1.7%) after 151 y (Dendooven et al., 2000).

It appears that the size of microbial biomass is quite stable among different treatments. Thus, the size of active SOC pool was estimated by multiplying soil live biomass by three, 1.6 □ 3 = 5%. The size of the soil slow pool is chosen as 55% according to Metherell et al. (1993) and the rest (40%) is the soil passive pool.

Model evaluation

First, simulated values of daily CO_2 flux were compared graphically with observations (and their standard errors) for each treatment. Then, simulated daily CO_2 flux, total CO_2-C evolved and soil mineral N at the end of the experiment were analysed by a series of statistical methods. The association between simulated and measured values was assessed by r^2. Systemic errors were determined by the sum of squares attributable to lack of fit (LOFIT) (Whitmore, 1991). This method allows 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). Relative error (RE) and the mean difference between measurement and simulation (M) were calculated to evaluate consistent errors (Addiscott and Whitmore, 1987). The maximum error between predicted and observed values (ME) was calculated and compared with RMSE □ _ /100, where RMSE is root mean square error (Loague and Green, 1991) and _ is the mean of observation. A value of ME that is much greater than RMSE □ _ /100, could indicate an erroneous observation or may point to a particular aspect of the model that requires further development (Smith et al., 1996).

RESULTS AND DISCUSSION

Model Weaknesses and Model modifications

In general, the CENTURY model appeared to perform reasonably well in predicting the trend of soil respiration under different straw managements and soil moisture conditions (Fig. 1), indicating that the model is structurally sound. However, discrepancies between model predictions and observed values in some treatments are obvious. Those discrepancies revealed some weaknesses of the model and pinpointed areas where the model can be modified for improvement.

Temperature factor

The CENTURY model underestimated CO_2 fluxes for the NW and IW treatments (Fig. 1a, c). The soil has the mineral N content of 18.4 mg N kg^{-1} soil at the beginning of the experiment (Curtin et al., 1998). Thus, in these two treatments, the decompositions are not limiting by the moisture condition and the availability of mineral N. The underestimated CO_2 fluxes are caused mainly by underestimated the decomposition rate at temperature 20 ^oC. According to the model, the temperature function used for calculating decomposition rate is expressed by an exponential function with the reference temperature of 35 ^oC. Based on the equation given in the model, the decomposition rate at 20 ^oC is only 51% of the rate at 35 ^oC. In testing the CENTURY model, Paustian et al. (1992) used 27 ^oC as the reference temperature to simulate SOC dynamics of an experiment in Sweden based on the assumption that soil microbes in that cold region (mean annual temperature is 5.4 ^oC) might have higher decomposition rate at lower temperatures than in the warmer mid-continental USA. Lomander et al. (1998) used a quadratic function to describe the response of decomposition rate to temperature. According to their equation, the relative decomposition rate is 0.65 at 20 ^{o}C with the reference temperature of 25 ^{o}C. Until a valid temperature function is available based on local experiment data, we assume that the relative decomposition rate of 0.65 is better than 0.51 used in the CENTURY model to describe the temperature effect at 20 ^{o}C in this area and use it for the modified model.

<u>N availability factor</u>

The greatest deviation between predicted CO_2 fluxes and measured values occurred in the SW treatment (Fig. 1e): the CENTURY model substantially overestimated the decomposition rate when straw was applied on the soil surface. In the CENTURY model, potential decomposition rates for the surface plant residue pools and surface microbial active pool are arbitrarily set at 20% lower than soil pools assuming moisture condition is less optimal on the surface (Parton et al., 1987). However, it is recognized that, in addition to the moisture factor, availability of N also influences the decomposition rate (Henriksen and Breland, 1999). It is relatively easy to simulate the N availability for SOC pools because soil mineral N at the same soil layer should be readily available for use in decomposition. The main N source for surface C pools is considered to be soil N obtained by fungal translocation (Beare et al., 1992). There is little information available on the quantities of N transferred to the soil surface. Frey et al. (2000) found that the annual N flux from the soil to surface-applied wheat straw in a NT field in Colorado, USA by filamentous fungi was 2.4 g m^{-2} and N flux rates mediated by fungi were constant over the period of their test (185 d after the placement of straw). The N flux would be expected to increase under high soil N availability (Holland and Coleman, 1987) and low initial residue N concentration (Frey et al., 2000). As the initial concentration of soil inorganic N and straw N in the study by Frey et al. (2000) were close to that in our experiment (Curtin et al. 1998), we modified the model by assuming that the daily rate of potential N supply from soil via fungal translocation for decomposition of surface straw is 6.6 mg m^{-2} (i.e., 2.4 g m^{-2} y^{-1}). In the calculation, the N availability was estimated daily for soil and soil surface separately. If the N availability was less than the demand for maximum decomposition rates of soil or surface pools, decomposition rates of these pools would reduce until the supply met the demand.

<u>Soil moisture factor</u>

The soil moisture factor (Fw) used in the CENTURY model to modify the potential decomposition rate is given by the following equation:

$$Fw=1.0 / (1.0 + 4.0 \times \exp(-6.0 \times RWC)) \qquad (1)$$

where RWC is defined as the ratio of the moisture content above the wilting point and the available water between the field capacity and the wilting point. According to the equation, the minimum Fw is 0.2 when the RWC = 0. We assumed that soil respiration was zero when RWC =0. Therefore, we changed the moisture function to:

$$Fw=1.0 / (1.0 + 10.0 \times \exp(-8.0 \times RWC)) \qquad (2)$$

Although the results were not significant when RWC was high, the new function improved model predictions when RWC was very low (Fig.1b, d, f).

Model Evaluation: The CENTURY model vs The modified model

Daily CO_2 fluxes

The modified model improved simulations under moist conditions, such as at the beginning of all treatments and the whole period for treatments of NW and IW (Fig. 1). These improvements are due to the change in relative decomposition rate with temperature. The improvement of the modified model is supported by lower LOFIT and ME for Treatment NW (Table 1). The value of M is very close to zero for the modified model, which means simulated and measured values are almost identical. The occurrence of the small fluctuations of daily CO_2 evolution (Fig. 1a) and the poor correlation between measured data and simulations (Table 1) are probably caused by the day-to-day drift of the equipment (LI-COR LI-6000 analyzer) as the measurement accuracy of LI-6000 is about ±10%.

The pattern of measured data of Treatment IW was matched by the CENTURY model (Fig. 1c) and the associations between simulated and measured values (r^2) was significant (Table 1), indicating that the structure of the model is appropriate. However, the CENTURY model underestimated respiration during most of the experiment. Changing the temperature parameter improved the simulation significantly. Both LOFIT and M values were reduced (Table 1). The maximum error (ME) of the modified model occurred at the first day after watering as the prediction was higher than the observation (Fig. 1c). It seems that the straw decomposition does not reach the potential rate immediately after the watering because the fungi require several days to multiply on the straw. This model is not able to simulate this lag phase in CO_2 production.

Improvements of the modified model in simulations for Treatments ND and ID can be seen graphically (Fig. 1b, d). All r^2, LOFIT, RE and M values were improved for both treatments as a result of model modification (Table 1). The relatively high LOFITs were mainly caused by slightly overestimating respiration before the second watering for ND (Fig. 1b) and slightly underestimating it after second watering of ID (Fig. 1d). Overall, differences between simulated and observed values were very small (0.1-0.2 g m^{-2} day^{-1}). Similar to treatment IW, the maximum error in treatment ID for the modified model occurred at the first day after watering.

The CENTURY model overestimated CO_2 fluxes for treatments of straw applied on the soil surface under both soil water conditions (SW and SD, Fig. 1e, f) and they were not improved by modifications of temperature parameter and moisture function (data not shown). Results from the modified model indicate that soil mineral N was always sufficient to meet the potential decomposition rate of SOC pools in all treatments in this experiment and the modified model successfully simulated the daily CO_2 fluxes of Treatment SW (Fig. 1e). Most of the statistical parameters for the modified model were improved compared to the original CENTURY model (Table 1). The consistent error was not significant (RE and M) and the M value was very close to zero which means the simulated and measured values were almost identical. Although the LOFIT value was still significant and the r^2 was low, this was possibly due to measurement fluctuations (Fig. 1e).

Although the simulation is also improved by the modified model for Treatment SD especially for ME (Table 1), simulated values are still higher than observed values during most of experiment (Fig. 1f). The reason is possibly that the moisture content of surface straw is lower than soil moisture and it is not appropriate to use soil moisture to describe the moisture status of surface C pools. Assuming decomposition rates of soil SOC pools are the same for Treatments SD, ID and ND are the same, observed daily surface decomposition of Treatment SD is only about 25% of Treatment SW. The simulation could be improved if the moisture content of surface residue was known.

Total CO_2 emissions

The modified model greatly improved simulation of total CO_2-C evolution (Figure 2). The test of r^2 was more significant ($P < 0.001$) than the CENTURY model and the regression line was close to a 1:1 fit. Other statistical values were also improved, especially for LOFIT and ME (Table 2). These data indicate that this model successfully estimated total soil respiration for most of the treatments under conditions of this study, in spite of some daily discrepancies between measured and simulated values. The modified model still overestimated total CO_2 emission for Treatment SD because the dryness of surface straw was not used to calculate the moisture parameter.

Soil mineral N

The modified model improved the simulation of soil mineral N, especially for RE (Fig. 3 and Table 2). Both models underestimated the soil mineral N for most of the treatments and the reason is unknown. However, the linear relationship between measured and simulated values indicates that the structure of the CENTURY is sound and could be further improved.

CONCLUSION

The CENTURY model appeared to be structurally sound in predicting the trend of soil respiration under different straw managements and soil moisture conditions. However, some weaknesses were revealed in this study and the modified model improved significantly the model performance. Modifications of the CENTURY model were made to the temperature factor, N availability factor and moisture function that in turn modify the potential decomposition rate. The decomposition of surface straw was found to be closely related to N availability and moisture conditions. In this study, the decomposition of incorporated straw was not limited by N availability, however, it may occur in situations where soil mineral N is low (Henriksen and Breland, 1999). Further testing and modification may be needed to address this problem. Also, to improve the estimation of decomposition rate for surface-placed residue, the moisture status of the residue should be determined.

ACKNOWLEDGMENTS

Technical assistance in computer programming by E. Chan and J.Y. Lou is greatly appreciated.

REFERENCES

Addiscott, T.M., and A.P. Whitmore. 1987. Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. J. Agric. Sci. Camb. 109:141-157.

Beare, M.H., R.W. Parmelee, P.F. Hendrix, W. Cheng, D.C. Coleman, and D.A. Crossley. 1992. Microbial and faunal interactions and effects on litter nitrogen and decomposition in agroecosystems. Ecol. Monogr. 62:569-591.

Campbell, C.A., E.G. Gregorich, R.P. Zentner, G. Roloff, H.H. Janzen, K. Paustian, W. Smith, B.C. Liang, and B.G. McConkey. 1999. Carbon sequestration on the Canadian prairies - Quantification of short-term dynamics. ASA Annual Meetings in Baltimore, MD. USA. October 1998.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F.B. Dyck, F. Selles, and D. Curtin. 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. Can. J. Soil Sci. 75: 449-458.

Campbell, C.A., E.A. Paul, and W.B. McGill. 1976. Effect of cultivation and cropping on the amounts and forms of soil N. Pages 7-101 *in* Proc. Western Canada Nitrogen Symposium, 19-21 Jan. Calgary AB.

Campbell, C.A., and R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. Soil Sci. Soc. Am. J. 57: 1034-1040.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan - Effect of crop rotations and fertilzers. Can. J. Soil Sci. 80:179-192.

Curtin, D., F. Selles, H. Wang C.A. Campbell, and V.O. Biederbeck. 1998. Carbon dioxide emissions and transformation of soil carbon and nitrogen during wheat straw decomposition. Soil Sci. Soc. Am. J. 62: 1035-1041.

Dendooven, L., E. Murphy, and D.S. Powlson. 2000. Failure to simulate C and N mineralization in soil using biomass C-to-N ratios as measured by fumigation extraction method? Soil Bio. Biochem. 32:659-668.

Frey, S.D., E.T. Elliott, K. Paustian and G.A. Peterson. 2000. Fungal translocation as a mechanism for soil nitrogen inputs to surface residue decomposition in a no-tillage agroecosystem. Soil Biol. Biochem. 32:689-698.

Henriksen, T.M., and T.A. Breland. 1999. Nitrogen availability effects on carbon mineralization, fungal and bacterial growth, and enzyme activities during decomposition of wheat straw in soil. Soil Biol. Biochem. 31: 1121-1134.

Holland, E.A., and D.C. Coleman. 1987. Litter placement effects on microbial and organic matter dynamics in an agroecosystem. Ecology 68:425-433.

Janzen, H.H., C.A. Campbell, R.C. Izaurralde, B.H. Ellert, N. Juma, W.B. McGill, and R.P. Zentner. 1998. Management effects on soil C storage on the Canadian prairies. Soil Till. Res. 47:181-195.

Loague, K., and R.E. Green. 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. J. Contamin. Hydro. 7:51-73.

Lomander, A., T. Kätterer, and O. Andrén. 1998. Modelling the effects of temperature and moisture on CO_2 evolution from top- and subsoil using a multi-compartment approach. Soil Biol. Biochem. 30:2023-2030.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279-288.

Metherell, A.K., L.A. Harding, C.V. Cole, and W.J. Parton. 1993. CENTURY soil organic matter model environment. Technical Documentation, Agroecosystem Version 4.0. Great Plains System Research Unit Technical Report No. 4. USDA-ARS.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173-1179.

Paustian, K., W.J. Parton, and J. Persson. 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J. 56:476-488.

Smith, J., P. Smith, and T. Addiscott. 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. *In* Evaluation of Soil Organic Matter Models. D.S.

Scholes, M.C., D. Powlson, and G. Tian. 1997. Input control of organic matter dynamics. Geoderma 79:25-47.

Whitmore, A.P. 1991. A method for assessing the goodness for computer simulation of soil processes. J. Soil Sci. 42: 289-299.

Table 1. Assessments for simulations on daily CO_2 -C fluxes by r^2, LOFIT, RE, M and ME.

Treatment	r^2	LOFIT	RE	M	ME	R	ME-R
				-------------	g m^{-2} day^{-1}		-------------
NW							
CENTURY	0.22	0.46	10.2‡	0.05	0.18	0.10	0.08
Modified	0.23	0.33	-14.2‡	-0.02§	0.13	0.08	0.05
ND							
CENTURY	0.85***	0.49†	-30.4‡	0.02§	0.30	0.09	0.21
Modified	0.86***	0.23†	-14.1‡	0.01§	0.23	0.06	0.17
IW							
CENTURY	0.88***	1.70†	5.9‡	0.09	0.48	0.18	0.30
Modified	0.87***	1.03	-7.7‡	-0.05§	0.45	0.15	0.30
ID							
CENTURY	0.90***	2.71†	-13.6‡	0.08§	0.48	0.19	0.29
Modified	0.91***	1.51†	4.6‡	0.04§	0.48	0.14	0.34
SW							
CENTURY	0.32*	4.59†	-57.0	-0.28	0.55	0.31	0.24
Modified	0.07*	0.40†	-3.0‡	0.00§	0.26	0.09	0.17
SD							
CENTURY	0.76***	5.37†	-177.1	-0.24	0.57	0.27	0.30
Modified	0.72***	1.40	-109.5	-0.10	0.22	0.14	0.08

LOFIT: lack of fit.
RE: Relative error.
M: The mean difference between measurement and simulation.
ME: The maximum error between predicted and observed values.
R: RMSE □ _/100 (RMSE is root mean square error and _ is the mean of observation). *, *** Significant at 0.01 and 0.001 probability levels, respectively.
† Simulated values are significantly different from observed values ($P < 0.05$) by *F* test.
‡ Simulated and measured values are equivalent at 0.05 probability level by *t* test.
§ Simulations and observations are coincident at 0.05 probability by *t*-test.

Table 2. Assessments for simulations on total CO_2 -C emission and soil mineral N by r^2, LOFIT, RE, M and ME.

Treatment	r^2	LOFIT	RE	M	ME	R	ME-R
			----------------	$g\ m^{-2}$	----------------		
Total CO_2 emission							
CENTURY	0.73*	1377.7†	-15.8‡	-2.4§	15.9	8.8	7.1
Modified	0.99***	33.5	-0.6‡	-3.8§	2.8	1.4	1.4
Soil mineral N							
CENTURY	0.88**	6.3†	22.3	0.5	1.0	0.6	0.4
Modified	0.90**	3.9†	17.4‡	0.4	0.8	0.5	0.3

LOFIT: lack of fit.
RE: Relative error.
M: The mean difference between measurement and simulation.
ME: The maximum error between predicted and observed values.
R: RMSE _/100 (RMSE is root mean square error and _ is the mean of observation). *, **, *** Significant at 0.05, 0.01 and 0.001 probability levels, respectively.
† Simulated values are significantly different from observed values ($P < 0.05$) by F test.
‡ Simulated and measured values are equivalent at 0.05 probability level by t test.
§ Simulations and observations are coincident at 0.05 probability by t-test.