CQESTR: A simple model to estimate carbon sequestration in tropical soils

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Resumo – CQESTR simulates the effect of management practices on soil organic carbon (SOC) stocks. The beta version of the model had been calibrated and validated for temperate regions. Our objective was to evaluate the CQESTR model performance for simulating carbon dynamics as affected by tillage practices in two tropical soils (Ultisol and Oxisol) in southeastern and northeastern Brazil. In the southeast (20.75 S 42.81 W), tillage systems consisted of no tillage (NT); reduced tillage (RT) (one disc plough and one harrow leveling [RT1] or one heavy disc harrow and one harrow leveling [RT2]); and conventional tillage (CT) (two heavy disc harrows followed by one disc plough and two harrow levelings). In the northeast (7.55 S 45.23 W), tillage systems consisted of NT, RT (one chisel plow and one harrow leveling), and CT (one disk plow, two heavy disk harrowings, and two harrow levelings). CQESTR underestimated SOC at both sites, especially under NT systems, indicating that adjustments (e.g., the inclusion of clay mineralogy factor) are necessary for more accurate simulation of SOC in the tropics. In spite of this, measured and simulated values of SOC in the 0–20 cm depth were well correlated (southeast, R^2 =0.94, p<0.01; northeast, R^2=0.88, p<0.05). The model estimated carbon emissions varying from 0.36 (NT) to 1.05 Mg ha^{-1} year^{-1} (CT) in the southeast and from 0.30 (NT) to 0.82 (CT) Mg ha^{-1} year^{-1} in the northeast. CQESTR showed acceptable performance to predict SOC dynamics in two tropical soils of Brazil.

Introduction

Simulation models are important tools for evaluating long-term effects of management systems on soil organic matter stocks and carbon sequestration potential. In such models, the relationships among several components are described explicitly, as is the influence of environmental conditions. Following appropriate calibration and validation, models can be used to study SOM dynamics and to explore the possibilities for modification of SOM content and/or composition through various intervention measures in the system (Shibu *et al.* [1]). Several SOM simulation models have been developed and evaluated during the past 30 years, for example, Century (Parton *et al.* [2]), RothC (Coleman & Jenkinson, [3]) and EPIC (Izaurralde *et al.* [4]). However, mechanistic models are often too complex and show multicompartmental structure based on qualitative concepts rather than measurable entities, and the required parameters or input variables are generally difficult to obtain. Thus, it is important that simpler but mechanistic SOM models be developed and validated under field conditions (Bruun *et al.* [5]). CQESTR is a simple model that simulates the effect of management practices on soil organic carbon stocks. However, in spite of simplicity, few studies have used it in temperate regions (Rickman *et al.* [6]) and none in tropical regions. The objective of this study was to evaluate CQESTR for simulating organic carbon dynamics in tropical soils of Brazil under no-tillage and plowed systems.

Key-Words: Soil organic matter, no-tillage, simulation model

Material and Methods

The model was evaluated with data from two experiments in Brazil. One experiment was established in 1985 at the Federal University of Vicosa Experimental Station, in Coimbra, Minas Gerais State (20.75 S 42.81 W). The other experiment was established in 1994 at Boa Esperanca Farm, in Baixa Grande do Ribeiro (BGR), Piauí State (7.55 S 45.23 W). The mean annual air temperature and average rainfall are 19 °C and 1350 mm at Coïmbra and 25 °C and 1200 mm at BGR. Soils at the Coimbra field are Typic Hapludults and classified as "Argissolo Vermelho–Amarelo" in the Brazilian Classification scheme. The surface horizon (Ap) has a clay texture (460 g clay kg^{-1}), low pH (5.1), and 1.73% C. Soils at the BGR field are Typic Hapludoxs, which is referred to as "Latossolo Vermelho–Amarelo" in the Brazilian classification scheme, with a clay texture (560 g clay kg^{-1}), low pH (5.0), and 1.52% C in the surface horizon.

In Coimbra, the area was covered by Atlantic Forest (AF) until 1930. After that, the land was cultivated for 54 years with major crops, such as maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.). An experiment was begun in 1985 that consisted of four tillage systems, arranged in a complete randomized block design, with four replications. Tillage treatments were 1) No tillage (NT); 2)

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Reduced Tillage-disk plow (RT1); 3) Reduced Tillage–heavy disk harrow (RT2) and; 4) Conventional Tillage (CT)-heavy disk harrow plus disk plowing. In BGR, the area was originally covered by Cerrado (CER) vegetation (Savannah Forest) until 1990 and then was cultivated for 4 years with soybean under conventional tillage. An experiment started at the end of 1994 consisting of three tillage systems arranged in a complete randomized block design with four replications. The soil was cultivated with soybean, maize, or rice (*Oryza sativa* L.) during the wet season and with millet (*Pennisetum glaucum* L.) as a cover crop during the dry season. Tillage systems were 1) NT; 2) RT—chisel plow and one harrow leveling, 3) CT—one disk plow, two heavy disk harrowings and two harrow levelings. Adjacent areas (100 m distance) with the same soil type and native vegetation were selected as reference plots at both locations. These plots were under secondary AF and native CER at Coimbra and BGR, respectively

CQESTR works on a daily time-step and can perform long-term simulations (100 years). The model balances the effect of crop residue or soil amendments additions and losses by microbial oxidation with native SOM. Residue decomposition is simulated by an exponential function driven by cumulative heat units, with appropriate empirical coefficients for the type of residue, nitrogen content, and incorporation into the soil by tillage. The following information was required by CQESTR: Crop biomass (above and below ground), dates of all residues or amendment additions and tillage operation, fraction of pre-tillage residue weight remaining on the soil surface after each tillage, depth of tillage, nitrogen content of residue at decomposition initiation, average daily air temperature expected throughout the time of interest, an approximate date for the first significant rain after harvest, number and thickness of soil layers, organic matter content, and bulk density of each layer.

The agreement between simulated (Y) and measured (X) values after model calibration was assessed with a) linear regression relating simulated to measured values with intercept not significantly different from zero and slope not significantly different from unity and b) mean squared deviations (MSD) and its components (inequality of means [IM], nonunity mean square [NU] and lack of correlation [LC]). Carbon sequestration potential estimated by CQESTR (0–20 cm) was compared to measured values in 2000 (Coimbra) and 2006 (BGR).

Results and Discussion

CQESTR underestimated SOC stocks for both sites (Fig. 1). This underestimation has been observed in others models (e.g., Century) and is directly related to lack of important mechanisms of C stabilization in tropical soils. As many tropical soils are dominated by variable-charge minerals with low cation exchange capacity (CEC), organic matter becomes very important for the nutrient status of the soils (Mendonça & Rowell [7]). Since the climatic conditions of the tropics promote fast soil organic matter decomposition, especially after forest clearing, tropical soils would be very poor in organic matter without this stabilization process. In spite of this, correlation is good, especially for Ultisol (R^2=0.94 $p<0.01$) (Fig. 1). This conclusion is in agreement with that obtained by Hong–Jun *et al.* [8]. They evaluated CQESTR at seven sites in China and reported a good correlation (R^2=0.94; $p< 0.05$) between simulated and measured values. The highest contributing component of MSD was inequality of means for both sites (75% and 82%) followed by the lack of correlation (Ultisol) and nonunity mean square (Oxisol) (Fig. 1). These results help better evaluate CQESTR performance. Measured and simulated values were highly correlated (low LC), but measured and simulated means were different (high IM), and slope was different from unity at Oxisol (high NU), indicating that the model is better able to simulate SOC dynamics under different management systems in some tropical soils than others.

For the Ultisol, CQESTR estimated that tillage systems are emitting 0.36 and 1.05 Mg C ha^{-1} $year^{-1}$ under NT and CT, respectively. Measured values also indicated that all tillage systems (including NT) emitted C; however, they were smaller in magnitude (Table 1). These estimates differ from others reported elsewhere showing carbon sequestration under no-tillage systems. We used C stocks at the beginning of the experiment as a reference for calculations. On the other hand, if estimates for 2000 were based on C stocks for NT and CT, C sequestration on the order of 0.47 (simulated) and 0.48 Mg ha^{-1} $year^{-1}$ (measured) would be reported for the 20-cm depth. When estimates are based on the difference between NT and CT, they agree well with published sequestration rates of 0.52 Mg ha^{-1} $year^{-1}$ for Ultisols in Brazil (Lovato *et al.* [9]).

In the Oxisol, C emissions were also observed, and ranged from 0.30 (NT) to 0.82 (CT) when estimated by CQESTR, and from 0.14 (NT) to 0.84 Mg ha^{-1} $year^{-1}$ (CT) when calculated from measured values. Like the Ultisol, the highest difference between simulated and measured values was observed in the no-tillage system (53%) compared with conventional (2%) and reduced (4%) tillage systems (Table 1). Considering SOC stocks in conventional tillage plots as the baseline, in 2006, NT estimated and measured annual C sequestration rates were 0.18 and 0.38 Mg ha^{-1} $year^{-1}$, respectively. Emission or sequestration rate estimated by CQESTR showed that the model simulated a more accurately reduced and conventional tillage than a no-tillage system. However, since CQESTR is a simpler model with fewer input variables, these results can be considered acceptable

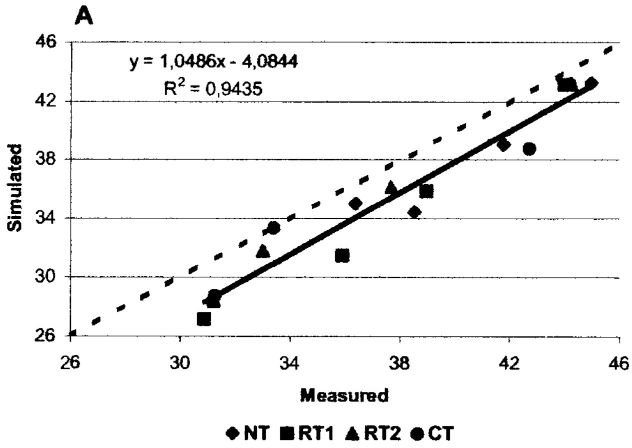
Conclusions

The CQESTR model simulations in general underestimated SOC at two study sites in Brazil.

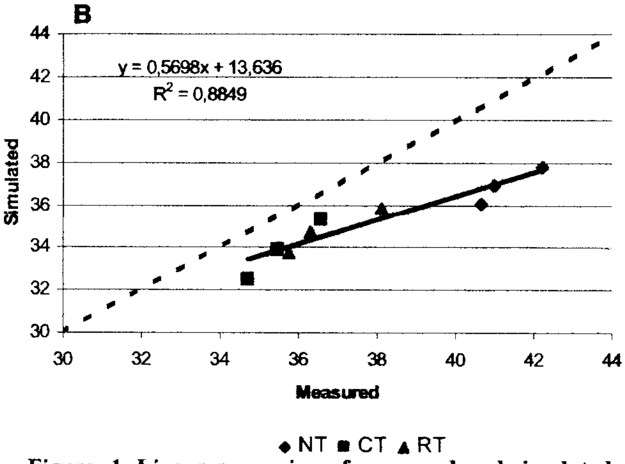
Table 1. Carbon emission estimated by CQESTR and by measured values in an Ultisol (Coimbra) under no tillage (NT), reduced tillage (RT1: disk plow; RT2: heavy disk harrow), and conventional tillage (CT) and in an Oxisol (BGR) under NT, *reduced tillage* (RT), *and CT at 0–20 cm depth.*

Tillage Systems	C stocks			Rate [1]	C Emission
	Initial	Final	Varation Δ		
	Mg ha^{-1}			Mg ha^{-1} year^{-1}	
			AVA (Coimbra)		
CQESTR					
NT	43,4	34,79	-8.60	-0.53	-0.36
RT1	43,4	28,45	-14.94	-0.93	-0.96
RT2	43,4	27,18	-16.21	-1.01	-1.05
CT	43,4	28,80	-14.59	-0.91	-0.94
Measured					
NT	44,0	38,54	-5.46	-0.34	-0.17
RT1	44,0	31,23	-12.77	-0.79	-0.82
RT2	44.0	30,90	-13.10	-0.82	-0.86
CT	44.0	31,24	-12.76	-0.79	-0.82
			LVA (BGR)		
CQESTR					
NT	42,7	36,07	-6.63	-0.51	-0.30
CT	42,7	32,53	-10.17	-0.78	-0.82
RT	42,7	33,75	-8.95	-0.69	-0.72
Measured					
NT	45,1	40,68	-4,42	-0.34	-0.14
CT	45,1	34,72	-10,38	-0.80	-0.84
RT	45,1	35,76	-9,34	-0.72	-0.75

[1] Contribution of 6 Mg ha^{-1} from cover crop (0.17 and 0.20 Mg ha^{-1} year^{-1} for Ultisol and Oxisol, respectively, considering 45% C) was assumed in no-tillage system (Salton et al., 2005) and a fuel additional C emission of 0.045 Mg ha^{-1} year^{-1} and 0.031 Mg ha^{-1} year^{-1} for conventional and reduced tillage, respectively (Dieckow, 2004).



Error component	Absolute value	Relative value %
Square bias	4.99	74.7
Nonunity slope	0.06	0.90
Lack of correlation	1.63	24.4
Mean square deviation	6.68	100



Error component	Absolute value	Relative value %
Square bias	7.06	82.1
Nonunity slope	1.25	14.5
Lack of correlation	0.29	3.4
Mean square deviation	8.60	100

Figure. 1. Linear regression of measured and simulated soil organic carbon in the 0–20 cm layer in an Ultisol (Coimbra) (A) and Oxisol (BGR) (B). The components of the mean square deviation are included. NT:no tillage; RT1: reduced tillage - disk plow; RT2: reduced tillage - heavy disk harrow; CT - conventional tillage (CT); RT: reduced tillage.

Additional studies are needed to improve the model estimates, and further adjustments might be necessary, such as consideration of clay mineralogy. Nevertheless, the model showed acceptable performance to predict SOC dynamic in two tropical soils of Brazil.

References

[1] Shibu, M.E., Leffelaar, P.A., Van Keulen H., Aggarwal, P.K., 2006. Quantitative description of soil organic matter dynamics—a review of approaches with reference to rice-based cropping systems. *Geoderma* **137**, 1–18.

[2] Parton, W.J., Schimel, D.S., Cole C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Sci. Soc. Am. J.,* **51**, 1173–1179, 1987.

[3] Colleman, K., Jenkinson, D.S., 1996. Roth,C. 26.3—a model for the turnover of carbon in soil. In: Polwson, T.S., Smith, P., Smith, J.U. (Eds.),. *Evaluation of Soil Organic Matter Models Using Existing Long Term Datasets*. NATO ASI, Series I, Vol. 38. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 237–246.

[4] Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J., Quirogas, Jakas, M.C., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. *Ecological Modelling* **192**, 362–384.

[5] Bruun, S., Christensen, B.T., Hansen, E.M., Magrid, J., Jensen, L.S., 2003. Calibration and validation of the soil organic matter dynamics of the Daisy model with data from the Askov long-term experiments. *Soil Biol. Biochem.* **35**, 67–76

[6] Rickman, R.W., Douglas Jr., C.L, Albrecht, S.L., Bundy, L.G, Berc, J.L., 2001. CQESTR: a model to estimate carbon sequestration in agricultural soils. *Journal of Soil and Water Conservation* **56**, 237–242.

[7] Mendonça, E.S. de, Rowell, R.L., 1996. Mineral and organic fractions of two oxisols and their influence on effective cation-exchageable capacity. *Soil Sci. Soc. Am. J.* **60**, 1888–1892.

[8] Hong-Jun L., Bao-Guo, L., You-Lu, B., Yuan-Fang H., Yi-Zhong L., Gui-Tong L., 2006. Modeling soil organic matter dynamics under intensive cropping systems on the Huang-Huai-Hai Plain of China. *Pedosphere.* **16**, 409–419.

[9] Lovato, T., Mielniczuck, J., Bayer, C., Vezzani, F., 2004. Adicão de carbono e nitrogênio e sua relacão com os estoques no solo e com o rendimento do milho em sistemas de manejo. *Rev. Bras. Ci. Solo* **28**, 175–187.

[10] Salton, J.C., Mielniczuk, J., Bayer, C., Fabricio, A.C, Macedo, M.C.M., Broch, D.L, Boeni, M., Conceicao, P.C., 2005. Materia organica do solo na integracao lavoura-pecuaria em Mato Grosso do Sul. *Embrapa Agropecuária Oeste*. Dourados, Brazil. 57 pp.

[11] Dieckow, J., Bayer , C., Martin-Neto, L., Mielniczuk, J., 2004. Sistemas conservacionistas de preparo do solo e implicacõoes no ciclo do carbono. *Embrapa Instrumentacão Agropecuária.* Sao Carlos, Brazil, 17 pp.