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Simulation Model to Estimate Carbon Sequestration under Management Systems in Tropical Soils of Brazil

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ABSTRACT

Soil organic carbon (SOC) represents a major pool of carbon within the biosphere and acts as source and a sink for carbon and nutrients. Several simulation models have been developed and evaluated to estimate SOC stocks in different agroecosystems such as, CENTURY or ROTHC which are considered mechanistic, complex and based on qualitative concepts rather than measurable entities. Because of this complexity, it is important that simpler but mechanistic SOC models, like CQESTR (a contraction of C sequestration), be developed and tested under several soil and climate conditions. CENTURY and CQESTR have been evaluated to estimate SOC stocks in different management systems. Particularly in tropical soils, both models have estimated an increase in the SOC stocks in the no-tillage compared to conventional tillage system. However, it is necessary to improve the model accuracy including important variables to tropical areas like soil structure or soil mineralogy.

Keywords: CENTURY, modeling, no-tillage, soil carbon stocks

Abbreviations: BIO, microbial biomass; **DP**, disc plow; **DPM**, decomposable plant material; **GIS**, geographic information system; **HH**, heavy harrow; **HHDP**, heavy harrow followed by disc plow; **HUM**, humified organic matter; **IOM**, inert organic matter; **NT**, no-tillage; **RMSE**, root mean square error; **RPM**, resistant plant material; **SOC**, soil organic carbon; **SOM**, soil organic matter; **TOC**, total organic carbon

CONTENTS

INTRODUCTION

Soils play a vital role in the cycling of carbon (C) from the atmosphere to the biosphere. The soil C pool comprises soil organic carbon (SOC) estimated at 1550 Pg (1 Pg $=10^{15}$ g) and soil inorganic C (SIC) approximately 950 Pg to 1 m depth. This total soil C pool of 2500 Pg is 3.3 times the atmospheric pool of 770 Pg and 4.1 times the vegetation pool of 620 Pg (Lal *et al*. 2006; Nair *et al.* 2009; Luo *et al.* 2010). However, cultivation of virgin soils, under intensive soil management, results in large losses of SOC (20-50%) usually as a result of a reduced turnover of soil organic matter (SOM) and consequent increase in the CO_2 emissions (Leite *et al*. 2003; Cerri *et al*. 2007a).

In tropical regions, where high temperatures and rainfall can increase SOM decomposition, the use of conservation management system, such as no-tillage and integrated crop livestock can reverse this process, favoring the recovery of SOC, increasing carbon sequestration, and hence, reducing the greenhouse effect (Lal 2004). Carbon sequestration is a natural process involving the net removal of CO_2 from atmosphere and storage in long-lived pools of C. Such pools include the aboveground plant biomass, belowground biomass such as roots, soil microorganisms and the relatively stable forms of organic and inorganic C in soils (Nair *et al*. 2008).

Simulation models can be useful for estimating, in short- and long-term, the influence of management practices on SOC stocks and C sequestration rate extrapolating these changes over large regions (Izaurralde *et al.* 2009). Among the several process-based models available, CENTURY (Parton *et al.* 1987); ROTHC (Coleman and Jenkinson 1993) or EPIC (Williams and Renard 1985; Izaurralde *et al.* 2006) can be considered the most robust and widely used (Galdos *et al.* 2009). However, these 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 (Shibu *et al.* 2006; Leite *et al*. 2009). Therefore, it is important that simpler but mechanistic SOM models, like CQESTR, be developed and validated under different soil and climate conditions (Lei *et al*. 2006). CENTURY and CQESTR have been evaluated in tropical soils of Brazil especially under different tillage systems to estimate soil carbon sequestration. The modeled and measured data were in good agreement for both models but the level of agreement would substantially improve if essential soil variable to tropical soils like soil structure and soil mineralogy could be included.

Received: 30 March, 2011. Accepted: 10 July, 2011.

Invited Mini-Review

CHARACTERISTICS OF SOIL ORGANIC MATTER SIMULATION MODELS USED IN BRAZIL

Process models are applied in order to permit examination beyond the limits set by measurements. The idea is that the exact process description of the models makes them applicable beyond the ranges of data behind them. This idea motivates the continuous development of models with a growing number of factors and complex internal structures (Palosuo 2008).

According to Shibu *et al.* (2006), simulation models to predict SOM changes have been developed since the 1940s, ranging from simple exponential decay functions (Henin and Dupuis 1945) to more complex functions with time-dependent relative decomposition rates in the 1960s (Kortleven 1963; Kolenbrander 1969). In the 1970s the first integrated soil-system models containing C/N cycling were reported by Dutt *et al.* (1972) and Beek and Frissel (1973) in the USA and Europe, respectively. These models were the first to combine C/N and related sub-processes of a soil-crop-nutrient system into an integrated model (Shaffer *et al.* 2001). Since then, a multitude of models has been developed, from simple regression equations to complex process-based models which varied in terms of complexity and mathematical description of the biological and geochemical processes involved. Battle-Aguiar *et al.* (2010) have divided SOM simulation models into process-oriented multi-compartment models (1), organism-oriented models (2), cohort models describing decomposition as a continuum (3) and a combination of model types 1 and 2. Process-oriented or compartment models can have a variable degree of complexity, from the simplest case with no compartment to more refined, multicompartment models with each compartment composed of organic matter with similar chemical composition of degradability. The development of a process-based model not only allows the simulation of SOC stocks or even agricultural greenhouse gas emissions at a range of scales up to national or global level, but also the exploration of potential mitigation strategies (Giltrap *et al.* 2010). CENTURY, ROTHC or CQESTR which have been evaluated in the tropical soils of Brazil are considered process-based model, although there are differences between them associated with C pools and fluxes.

CENTURY model was originally developed and tested on data sets mainly from grassland and wheat–fallow agriculture in the US Great Plains. The model represents plant growth, nutrient cycling, and SOM dynamics for both natural ecosystems (grassland, forest, and savanna systems) as well as agricultural systems. Soil nutrient cycling and SOM dynamics are simulated with greater detail, whereas plant growth and water movement are represented by relatively simpler submodels (Tornquist *et al.* 2009). Multiple pools or compartments, i.e. structural and metabolic related to plant residue and active, slow and passive associated to the soil, with specific residence times, are included. There is also a surface microbial pool, which is associated with decomposing surface litter. Active pool represents soil microbes and microbial products and has a turnover time ranging of months to a few years depending on the environment and sand content. The surface microbial pool turnover rate is independent of soil texture and it transfers material directly into the slow pool (turnover time of 20-50 years) which includes resistant plant material derived from the structural pool and soil-stabilized microbial products derived from active and surface microbe pools. The passive pool is very resistant to decomposition and includes physically and chemically stabilized SOM and has a turnover time of 400-1000 years (Ponce-Hernandéz 2004). Decomposition of all pools is described according to first-order kinetics with different relative rate constants per pool that vary for different systems like arable crops, grass and forest. Main input variables requires: (1) monthly precipitation; (2) monthly average maximum and minimum air temperature; (3) soil attributes (texture, bulk density); (4) lignin, N, S, and P content of plant material; (5) soil and atmospheric N inputs and; 6) initial soil C, N, P levels. Although considered relatively complex, especially due to the number of input variable, CENTURY have been used successful when tested in several temperate and tropical systems.

ROTHC model also is considered a model with a good accuracy and with several concepts similar to those in the CENTURY. It was tested in long term experiments on a range of soils and climatic conditions in Western and Central Europe. In a majority of cases, ROTHC was evaluated on long-term experimental sites with detailed descriptions of the sites conditions and treatments (Coleman *et al.* 1997; Smith *et al*. 1997; Falloon and Smith 2002; Barančíková 2007; Ludwig *et al.* 2007). In the model, plant material enters the soil via litter fall. Part of this material is returned to atmosphere via CO_2 (soil respiration) after passing through of five pools which includes inert organic matter (IOM), decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). All pools, except IOM, decompose by first-order decay. As reported by Shibu *et al.* (2006), CENTURY and ROTHC shows different conceptual soil C pools (active, slow and passive in CENTURY and humus and inert in ROTHC), with widely different residence times (few months, 25 years, 1000 years in CENTURY, and 50 and 50000 years in ROTHC). CENTURY's passive pool is larger than the inert organic matter (IOM) pool of RothC, both of which are resistant to decay. On the other hand, active and slow components in CENTURY and the BIO and HUM components in ROTHC are of the same order of magnitude. In another approach, Cerri *et al.* (2007) related that both models have similar structure, containing pools with a rapid turnover (month-year), moderate turnover (decadal) and slow turnover (millennial or inert). Input variables required to run ROTHC model are more easily obtained than CENTURY and includes mainly rainfall and open pan evaporation, air temperature and soil attributes (clay content and bulk density).

CQESTR, pronounced sequester, a contraction of C sequestration has been in continuous development since 2000. It is a process-based model considered simpler than CENTURY and ROTHC. With the goal of using readily available or easily obtainable inputs instead of detailed physical or chemical fractionation of C source, CQESTR was developed to simulate the effect of management practices on short and long-term trends of SOM and can be used to evaluate the environmental impacts of large-scale crop residue removal from agriculture (Liang *et al.* 2009). The model is easy to use and have showed good accuracy in estimating soil C trends especially in temperate regions, since that, in tropical soils, its use just has been recently evaluated (Leite *et al.* 2009). In CQESTR, each organic residue addition is a tracked separately, without partitioning, according to its placement on the surface or buried in the soil. The model operates on a daily step and its major input variables include the number and thickness of soil layers, organic matter content and bulk density of each layer, above-ground and below-ground crop biomass, tillage operations, monthly average air temperature, monthly precipitation, and nitrogen content of residues at the beginning of decomposition. Most of the required input data, including climate, is automatically extracted from existing crop management files associated with the C-factor files in the revised Universal Soil Loss Equation (RUSLE; Renard *et al*. 1996).

ESTIMATION OF SOIL ORGANIC CARBON STOCKS UNDER MANAGEMENT SYSTEMS USING CENTURY, ROTHC AND CQESTR MODELS

Soil organic matter simulation model have been evaluated in different management systems, especially in temperate regions. However, in tropical regions, the number of studies can be considered limited and restricted to the use of the CENTURY model. In Brazil, Leite *et al.* (2004) studied the effect of four tillage systems (no tillage (NT), disk plow

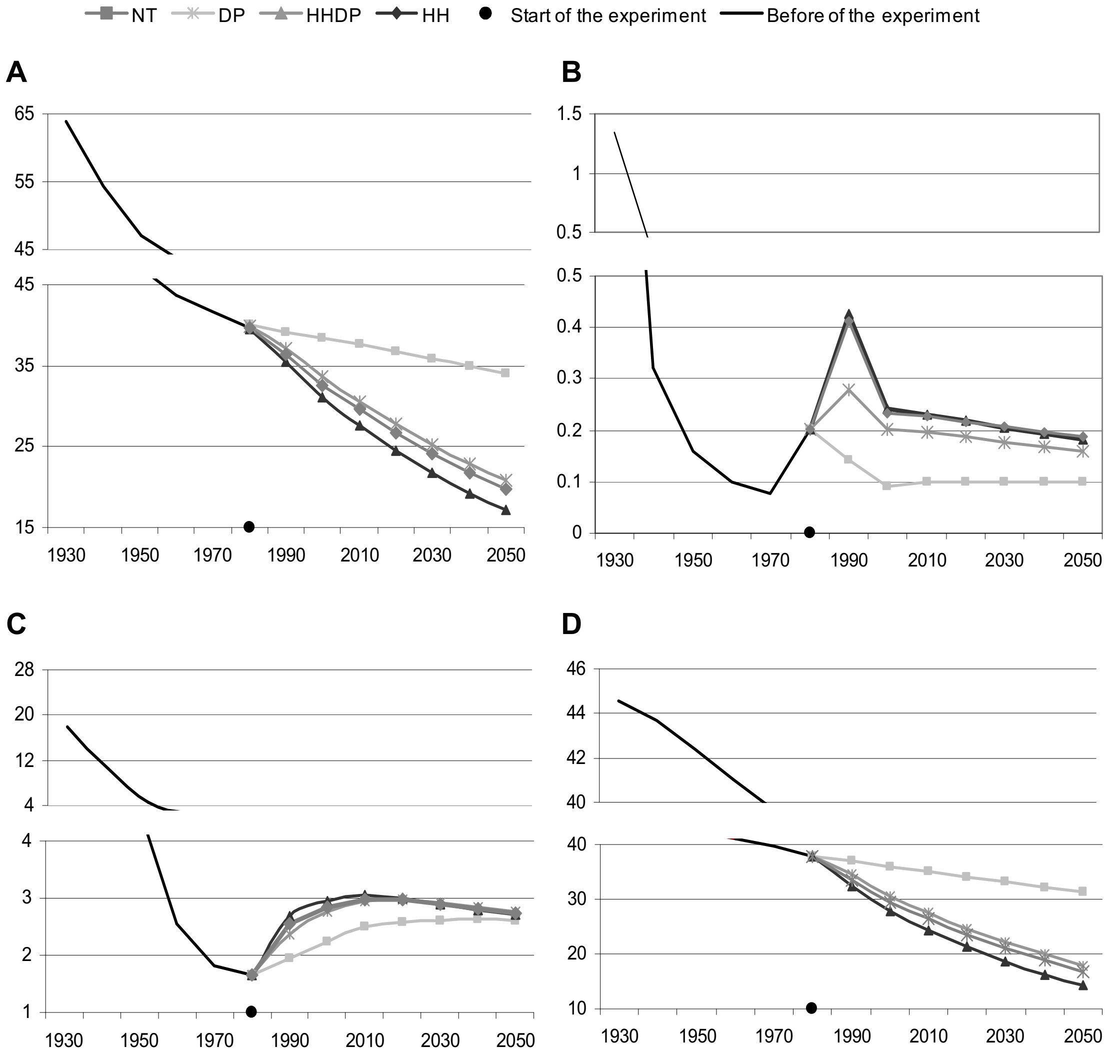

Fig. 1 Time variation of organic carbon stocks (TOC) (**A**) and active (**B**), slow (**C**), and passive (**D**) pools simulated by CENTURY in the no-till (NT), disc plow (DP), heavy harrow followed by disc plow (HHDP) and heavy harrow (HH) systems. Source: **Leite LFC, Mendonça ES, Machado PLOA** (2004) Simulating trends in soil organic carbon of an Acrisol under no-tillage and disc-plough systems using the Century model. *Geoderma* **120**, 283-295, ©2004, with kind permission of Elsevier, Amsterdam, the Netherlands.

(DP), heavy harrow (HH) and disk plow + heavy harrow (DPHH)) on total organic carbon (TOC) stocks estimated by laboratory methods and CENTURY model at an Ultisol located in the Minas Gerais state, southeastern region. The authors observed that tillage systems did not change the trend to decreasing stocks of carbon. Fifteen years after setting up the field experiment (2000), TOC stocks in the soil under NT, DP, HHDP and HH were 38, 32, 31, and 34 Mg ha^{-1}, respectively (**Fig. 1A**). This tendency continued mainly due to conventional plowed systems and in 2050 the projected TOC will be 34 Mg ha^{-1} in the soil under NT, and approximately 20 Mg ha^{-1} in the soils under DP, HHDP and HH. Despite these results, soils under NT system were the only ones to show a slight recovery in long term.

Similarly to TOC, there was a reduction of the soil carbon stocks of the active, slow and passive pools even with adoption of NT system which shows that although the soil has been under NT for 15 years, no soil disturbance without cover crop management hardly help to improve an increase of TOC in acidic tropical soils (**Figs. 1B-D**). Comparing observed and simulated TOC stocks, in 2000, it was observed that the difference in the NT system was very low (< 0.2%) and in the others systems, varied from 0.4 to 7% which is considered an excellent result. On the other hand, to active and slow pools there was an underestimation of the CENTURY active and slow pools explained by the lack of important chemical processes in acid tropical soils not considered by the model such as organic matter–Al complex relevant in the control of the Al toxicity and therefore in the soil organic matter mineralization (Haynes and Mokolobate 2001; Meda *et al*. 2001).

Other works were developed under Brazilian conditions with CENTURY to verify the model accuracy. Galdos *et al.* (2009) used CENTURY in sites from northeastern and southeastern region of Brazil (and other one from South Africa) to quantify the effect of sugarcane residue management in the temporal dynamic of soil C. The authors mentioned that the green cane management leads to higher C stocks in the long term than the system where crop residues are burned and that, considering all the sites, the model was accurate in simulating the temporal dynamics of soil C stocks under different trash, fertilizer and organic residue management ($R^2 = 0.89$) with difference below 12%. However, the model tended to a underestimate where mineral fertilizer was applied which can be attributed to the faster SOM decomposition simulated by CENTURY due to narrowing of the C/N ratio of the sugarcane litter when mineral N was added into the system.

Torquinst (2009) also applied the CENTURY model associated to geographic information system (GIS) to examine changes in SOC stocks since the inception of agriculture in a representative area within the main agricultural region of Rio Grande do Sul State, in southern Brazil. The results showed that there was a marked decrease in C stocks after conversion to agriculture, with losses of about 50% from 1900-1980 and that a tendency of stabilization in the SOC stocks and a slight increase after conservation agricultural practices such as reduced tillage and improved fertili-

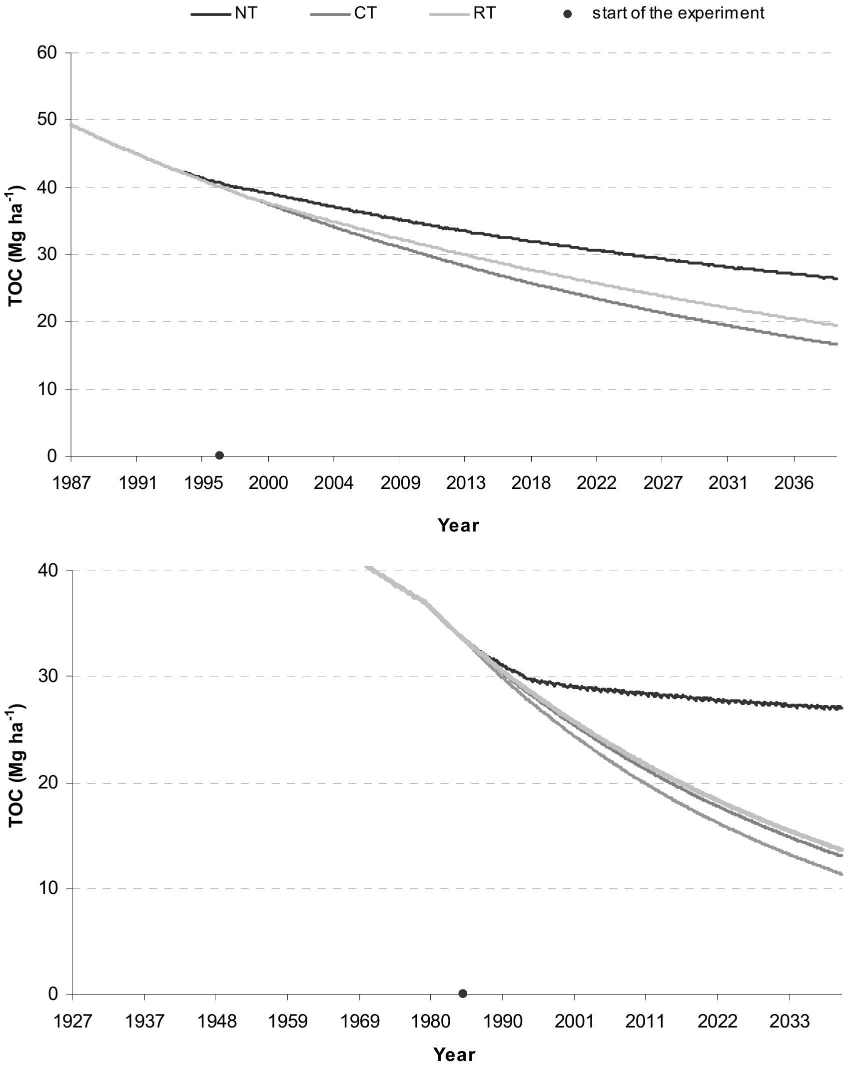

Fig. 2 Soil organic carbon dynamic (0–20 cm) simulated by CQESTR in an Ultisol (**A**) under no tillage (NT), reduced tillage (RT1: disk plow; RT2: heavy disk harrow), and conventional tillage (CT) and in an Oxisol (**B**) under NT, reduced tillage (RT) and CT. Source: **Leite LFC, Doraiswamy PC, Causarano HJ, Gollany HT, Milak S, Mendonça ES** (2009) Modeling organic carbon dynamics under no-tillage and plowed systems in tropical soils of Brazil using CQESTR. *Soil and Tillage Research* **102**, 118-125, ©2009, with kind permission of Elsevier, Amsterdam, the Netherlands.

zation was observed in the 1980s. In 1992, greater increase was observed with the advent of no-tillage system. Moreover, the authors reported that the model performance for most soils (Ustropept, very clayey Hapludox and clayey Hapludox under woodlands) was good. However SOC stocks were underestimated in loamy Hapludox and the clayey Hapludox originally under grasslands. This can be explained by the lack of an explicit treatment of clay mineralogy as related by the author and by Leite *et al.* (2004). Oxisols have mineralogy dominated especially by iron oxides such as these strongly bond to organic ligands, protecting, therefore, SOC from decomposition.

In the Brazilian Amazon conditions, Cerri *et al.* (2007b) evaluated ROTHC and CENTURY performance to estimate SOC changes under forest-to-pasture. Several chronosequences to represent different soil clay content, grass types and climatic condition were used. The models showed that, in the majority of the chronosequences, the conversion of Amazonian forest to well-managed pasture causes an initial decrease in the SOC stocks (0–20 cm) followed by a slow rise to levels exceeding those under native forest. According to the authors, all correlation coefficients (r) were greater than zero, showing positive correlation between simulated and measured values. Also, the calculated values close to zero for the mean difference between observation and simulation (M) indicate that consistent error was small. This can be corroborated by the root mean square error (RMSE), considered useful to compare errors in simulation made by different models (lower values of RMSE means a more accurate simulation) which showed, in the almost all cases, less than 20% (many around 10% or less). Therefore, based on the statistical methods, the authors reported that CENTURY and ROTHC showed a reasonable representation of the effect of land management on SOC stocks.

Leite *et al.* (2009) estimated a decrease in the SOC stocks after conversion of native forest to cropland (tillage systems) using CQSTER model. At Coimbra, southeastern Brazil (Ultisol), SOC stock in 1985 (beginning of the experiment) was 34 Mg ha^{-1}, which represents a 47% decrease with respect to SOC stocks under the Atlantic Forest. This reduction was greater than the 37% decrease estimated by CENTURY for the same experiment (Leite *et al.* 2004). However, if soil bulk density in 1985 is used for calculation of C stocks, the CQESTR estimate would be only 3% greater than the Century estimate. As with many SOM simulation models, CQESTR does not consider tillage-induced changes in bulk density; consequently, SOC stocks can be underestimated since bulk density generally decreases with tillage operations. The authors verified also that all tillage systems (no tillage (NT), reduced tillage (RTI: disk plow; RT2: heavy harrow)) and conventional tillage (disk plow+heavy harrow)) showed a decreasing trend in SOC stocks. In 2006, the values were 28.8, 23.7, 23.3, and 22.0 Mg ha^{-1}, for NT, RT2, RT1, and CT, respectively (**Fig. 2**). At Baixa Grande Ribeiro, Northeastern Brazil (Oxisol), CQESTR also estimated a decrease in SOC stocks after conversion from the Cerrado vegetation to cropland. SOC stock measured under native forest was 48 Mg ha^{-1}, while SOC stock was 42 Mg ha^{-1} at the beginning of the experiment, in 1994 (**Fig. 2**). A 10% decrease in SOC stocks at BGR was lower than the 47% decrease at Coimbra. According to the authors, this is probably because BGR has been under conventional tillage for a shorter time (4 years) and also because of higher soil clay content at BGR, since the model uses a lower decomposition rate for heavier soil texture. Also, this is an Oxisol with high variable charge from Fe and Al oxides that could have stabilized organic matter as previously mentioned. SOC stocks decreased even after tillage systems adoption. In 2006, the values estimated by the model were 36, 34 and 32 Mg ha^{-1} for NT, RT, and CT, respectively, which means a reduction of 16, 20, and 25% in SOC stocks since the beginning of the experiment which means that residue obtained from the cover crop (6 Mg ha^{-1}) added was not enough to increase SOC stocks.

In relation to CQESTR performance, the authors observed that, similarly to the others model tested in tropical soils, CQESTR underestimated SOC stocks for both sites. In spite of this, differences between simulated and measured values were considered small (Ultisol: 1.8-12%; Oxisol: 1.25-4.6%) especially under conventional tillage, showing that input residue to the soil mainly from cover crop, should be better represented by the model. Therefore, more studies are needed to evaluate the CQESTR model's performance for simulating SOC dynamics in tropical soils. Further adjustments, such as inclusion of clay mineralogy and organic matter interaction might be necessary to improve the model's estimates. Nevertheless, the model showed acceptable performance to predict SOC dynamic in two tropical soils of Brazil.

CONCLUSIONS

Simulation models have been useful to estimate soil organic carbon dynamic in several agroecosystems of Brazil. However, to improve the accuracy in tropical soils, these models should include input variables such as soil structure, mineralogy and exchangeable aluminum and mechanisms like organ-mineral interaction. Also, some important strategies should be considered: 1) Creation of a database that provide organize information scattered in Brazil especially associated to climate variables, essential to simulate in local scale; 2) Validation of simulation models for the different Brazilian environment and production system especially in the regional scale using GIS and remote sensing; 3) Development of simulation model from long-term experiment carried out in Brazil.

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