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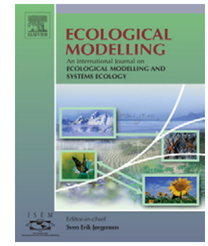

Simulating soil organic matter with CQESTR (v. 2.0): Model description and validation against long-term experiments across North America

Y. Liang[b], H.T. Gollany[a,*], R.W. Rickman[a,1], S.L. Albrecht[a], R.F. Follett[c], W.W. Wilhelm[d], J.M. Novak[e], C.L. Douglas Jr.[a,1]

[a] USDA-ARS, Columbia Plateau Conservation Research Center, P.O. Box. 370, Pendleton, OR 97801, United States
[b] Department of Biological and Agricultural Engineering, Cooperative Extension Service, University of Arkansas, Fayetteville, AR 72701-1201, United States
[c] USDA-ARS, Soil Plant Nutrient Research Center, Fort Collins, CO 80526, United States
[d] USDA-ARS, Agroecosystem Management Research Unit, Lincoln, NE 68583, United States
[e] USDA-ARS, Coastal Plains Soil, Water and Plant Research Center, Florence, SC 29501, United States

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ABSTRACT

Soil carbon (C) models are important tools for examining complex interactions between climate, crop and soil management practices, and to evaluate the long-term effects of management practices on C-storage potential in soils. CQESTR is a process-based carbon balance model that relates crop residue additions and crop and soil management to soil organic matter (SOM) accretion or loss. This model was developed for national use in U.S and calibrated initially in the Pacific Northwest. Our objectives were: (i) to revise the model, making it more applicable for wider geographic areas including potential international application, by modifying the thermal effect and incorporating soil texture and drainage effects, and (ii) to recalibrate and validate it for an extended range of soil properties and climate conditions. The current version of CQESTR (v. 2.0) is presented with the algorithms necessary to simulate SOM at field scale. Input data for SOM calculation include crop rotation, aboveground and belowground biomass additions, tillage, weather, and the nitrogen content of crop residues and any organic amendments. The model was validated with long-term data from across North America. Regression analysis of 306 pairs of predicted and measured SOM data under diverse climate, soil texture and drainage classes, and agronomic practices at 13 agricultural sites having a range of SOM (7.3–57.9 g SOM kg^{-1}), resulted in a linear relationship with an r^2 of 0.95 ($P < 0.0001$) and a 95% confidence interval of 4.3 g SOM kg^{-1}. Using the same data the version 1.0 of CQESTR had an r^2 of 0.71 with a 95% confidence interval of 5.5 g SOM kg^{-1}. The model can be used as a tool to predict and evaluate SOM changes from various management practices and offers the potential to estimate C accretion required for C credits.

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Abbreviations: CDD, cumulative degree-days; CT, conventional tillage; NT, no-tillage; SOC, soil organic C; SOM, soil organic matter; ST, sweep tillage.

* *Corresponding author.*
E-mail address: hero.gollany@ars.usda.gov (H.T. Gollany).
[1] Retired.

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1. Introduction

Management of soil organic matter (SOM) is critical for sustaining soil productivity and environmental quality. Soil organic matter influences soil physical, chemical, and biological properties and contributes to crop productivity and soil quality (Jenkinson, 1991; Lal, 1997). Soil is also a major pool (1720 Gt) in the cycling of carbon (C) from the atmosphere to the biosphere (Oades, 1988). There is a growing interest in utilizing soil to store C to reduce carbon dioxide (CO_2) levels in the atmosphere, with implications for the greenhouse effect and global warming (Lal et al., 1998; Paustian et al., 1995).

The amount of soil C in an agro-ecosystem is the net result of C input through primary production and deposition by wind or water erosion, C loss via respiration, loss by wind and water erosion, and translocation of dissolved organic C through soil (Campbell et al., 1996; Mertens et al., 2007). The turnover rate of different SOM compounds varies due to complex interactions between chemical, physical, and biological processes in soil. Soil C in its stable form as SOM responds gradually to agricultural management changes. Although changes in SOM have been detected over a short period of time (e.g. 5 years), when significant management change occurs and soil C pools are far from equilibrium (Conant and Paustian, 2002; West and Post, 2002), most SOM changes require a longer time period (e.g. at least 20 years) to be detectable by present analytical methods (Rasmussen et al., 1998). Simulation models can be useful for projecting short- and long-term effects of many factors that control SOM turnover.

Soil carbon models are needed to predict long-term effects of management practices on C accretion in soils and estimate the benefits of alternative management practices in reducing the greenhouse gas emissions and the impact on global warming. One of the first widely used SOM models (Jenkinson and Rayner, 1977; Jenkinson et al., 1991) divided soil C into active, slow and passive pools with different turnover times ($1/k$) (2, 50 and 1980 years). The model developed by Paul and van Veen (1978) and van Veen and Paul (1981) divided plant material into recalcitrant and decomposable fractions and included the concept of physical protection of SOM. They assumed that physically protected SOM has much lower decomposition rate than non-physically protected SOM. The CENTURY model (Parton et al., 1987; Paustian et al., 1992) established a general approach for splitting plant residue into structural and metabolic material as a function of the initial lignin to nitrogen ratio of the material. Parton et al. (1987) suggested that the soil silt plus clay content influences the turnover rate of the active SOM (higher for sandy soils) and the stabilization of active SOM into slow SOM. The NCSOIL model is a subroutine of NCSWAP (Nitrogen and Carbon Cycling in Soil, Water, Air and Plants) model to simulate N and C transformations in the soil (Molina et al., 1983, 1997) with residues defined into various pools ranging from labile to recalcitrant. It is a complex mechanistic model that integrates water flow dynamics, temperature, solute transport, tillage, crop growth, residue effects, and total and tracer N and C transformations (Gollany et al., 2004). The Environment Policy Integrated Climate (EPIC) model is a widely tested and adapted model originally built to quantify the effects of erosion on soil productivity (Williams et al., 1984). Since its inception, EPIC has evolved into a comprehensive agro-ecosystem model capable of simulating the growth of plant species, including crops, native grass and trees, grown in complex rotations and management operations, such as tillage, irrigation, fertilization and liming. Recently, C and N modules were added to EPIC (Izaurralde et al., 2006). The included C and N routines interact directly with soil moisture, temperature, erosion, tillage, soil bulk density, leaching, and translocation functions in EPIC (Izaurralde et al., 2006).

The detailed nutrient cycling models have typically been used to simulate the dynamics of C and N for a growing season, while the SOM models are used to simulate dynamics for longer time periods (i.e. decades). The major shortcoming of the above mentioned models “is that there is no generally acceptable way to determine the different SOM fractions, either chemically or physically, and thus it is impossible to directly measure SOM pools included in the models” (Parton et al., 1996).

The intergovernmental Panel on Climate Change (IPCC) has developed an inventory method that accounts for changes in soil carbon stocks related to changes in land use and/or agricultural management practices (IPCC, 1997). It is a first-order approach using simple assumptions about the effects of land use on carbon stocks, in the form of a series of coefficients based on climate, soil type, disturbance history, tillage intensity, and residue management. The method estimates SOC stocks over the first 20 years following a shift in management, during which the presumably greatest influence occurs (IPCC, 1997).

With the goal of using readily available input data at the field scale, the CQESTR model was developed to simulate the effect of management practices on short and long-term trends of SOM (Liang et al., 2008; Rickman et al., 2001, 2002). CQESTR also can be used to evaluate the environmental impacts of large-scale crop residue removal from agricultural land (Liang et al., 2008). Extensive evaluation of version 1.0 indicated that the model is easy to use and acceptable in predicting C trends in temperate regions with well drained soils (Rickman et al., 2002, 2005). Our objectives were (i) to revise the model, and make the model more applicable for wider geographic areas, including potential international application, by modifying thermal effect and incorporating soil texture and drainage effects, and (ii) to recalibrate the model with six long-term experiments with a range of climate, and drainage and soil texture classes, and validate it for an extended range of soil properties and climate conditions. The current version of CQESTR (v. 2.0) is presented with the necessary algorithms to simulate SOM at field scale.

2. Materials and methods

2.1. General description of the CQESTR model

CQESTR, pronounced sequester, a contraction of ‘C sequestration’ (meaning C storage), has been in continuous development since 2000. It is a process-based model that uses information stored in crop management files associated with the c-factor of the Revised Universal Soil Loss Equation