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Modifying the Soil and Water Assessment Tool to simulate cropland carbon flux: Model development and initial evaluation

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HIGHLIGHTS

- Expanding the SWAT model with the new capability of simulating land–atmosphere carbon exchange
- Model evaluation across spatially distributed sites using daily Eddy Covariance observations
- Comprehensive discussion of model performance as influenced by different factors

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ABSTRACT

Climate change is one of the most compelling modern issues and has important implications for almost every aspect of natural and human systems. The Soil and Water Assessment Tool (SWAT) model has been applied worldwide to support sustainable land and water management in a changing climate. However, the inadequacies of the existing carbon algorithm in SWAT limit its application in assessing impacts of human activities on CO_2 emission, one important source of greenhouse gasses (GHGs) that traps heat in the earth system and results in global warming. In this research, we incorporate a revised version of the CENTURY carbon model into SWAT to describe dynamics of soil organic matter (SOM)-residue and simulate land–atmosphere carbon exchange. We test this new SWAT-C model with daily eddy covariance (EC) observations of net ecosystem exchange (NEE) and evapotranspiration (ET) and annual crop yield at six sites across the U.S. Midwest. Results show that SWAT-C simulates well multi-year average NEE and ET across the spatially distributed sites and capture the majority of temporal variation of these two variables at a daily time scale at each site. Our analyses also reveal that performance of SWAT-C is influenced by multiple factors, such as crop management practices (irrigated vs. rainfed), completeness and accuracy of input data, crop species, and initialization of state variables. Overall, the new SWAT-C demonstrates favorable performance for simulating land–atmosphere carbon exchange across agricultural sites with different soils, climate, and management practices. SWAT-C is expected to serve as a useful tool for including carbon flux into consideration in sustainable watershed management under a changing climate. We also note that extensive assessment of SWAT-C with field observations is required for further improving the model and understanding potential uncertainties of applying it across large regions with complex landscapes.

1. Introduction

Watershed models have been widely used by researchers and decision makers to understand hydrologic, ecological, and biogeochemical processes as well as to examine effects of human activities and climate change/variability on water quantity and quality. The watershed model SWAT (Arnold et al., 1998) was designed to predict the short and long-term impacts of land management practices and climate change on water, sediment and agricultural chemical yields in complex watersheds with varying soils, land use and topographic conditions. It has been incorporated into the U.S. Environmental Protection Agency Better Assessment Science Integrating Point & Nonpoint Sources (BASINS, http://water.epa.gov/scitech/datait/models/basins/index.cfm) software package and is being applied by the United States Department of Agriculture (USDA) for the Conservation Effects Assessment Project (CEAP) (Van Liew et al., 2007; Richardson et al., 2008) across watersheds in the conterminous U.S. Researchers and water resource managers from over 90 countries have used SWAT in designing sustainable water management practices (https://swatmodel.tamu.edu; Gassman

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et al., 2007). In the applications of SWAT, most research has been focused on assessing water quality benefits (e.g. reduction of riverine sediment, pesticide, nitrogen and phosphorus) through simulations of best management practices (BMPs) across spatial locations within watersheds under current or future climate scenarios (https://www.card.iastate.edu/swat_articles/). However, the potential consequences of land management on terrestrial carbon (C) balance have rarely been assessed with SWAT and have not been linked to riverine processes.

Stabilizing the atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) at non-threatening levels for the biosphere is one of the most compelling modern-day issues with profound implications for the planet's environment (IPCC, 2007). Agricultural lands not only provide essential ecosystem goods (such as food, livestocks, and fiber) for humankind but also have a significant potential to sequester C and thus attenuate the rate of increase of atmospheric CO_2 (e.g. Lal et al., 1999; Allmaras et al., 2000; Thomson et al., 2006). It was estimated that agricultural technologies and practices can potentially mitigate ~5.5–6.0 Pg CO_2-eq yr^{-1} emissions at the global scale, of which 89% are from soil C sequestration (Smith et al., 2007). Overlooking carbon impacts of land management practices may lead to selection of BMPs causing unintended soil organic carbon (SOC) loss into the atmosphere. In addition, eroded and leached C entering rivers can cause degradation of water quality and subsequently impact negatively the health of human and aquatic ecosystems. Thus, it is critically important to consider C benefits or costs as an integral dimension of the sustainability of watershed management strategies. To the best of our knowledge, the current SWAT SOC model (Kemanian et al., 2011; Arnold et al., 2011) overlooks several key factors determining SOC dynamics, such as the lignin effect on litter decomposition, the movement of SOC with water flows, and loss of SOC through soil erosion. These weaknesses limit the applicability of SWAT for addressing C implications in designing sustainable watershed management practices.

There are many SOC models available for different purposes (McGill, 1996; Smith, 2001), such as CENTURY (Parton et al., 1994), the CArbon-Nitrogen-DYnamics model (CANDY; Franko et al., 1995), the Danish Simulation model DAISY (Hansen et al., 1991), the DeNitrification-DeComposition model (DNDC; Li et al., 1994), *ecosys* (Grant et al., 2001), and the Rothamsted organic carbon turnover model (RothC; Jenkinson and Coleman, 1994; Coleman and Jenkinson, 1996), the Soil Organic Matter Model (SOMM; Chertov and Komarov, 1997), and HSB-C (Fu et al., 2000). Among these, CENTURY has demonstrated consistent top performance based on test results using 12 long-term data sets characterized with inorganic fertilizer, organic manure, and various rotations (Smith et al., 1997). As well, model performance experiments conducted by Izaurralde et al. (2001) confirmed the capacity of CENTURY to provide satisfactory performance on depicting SOC dynamics across sites under different conditions. Its capability of simulating well SOC dynamics under both low- and high-N treatments (Kelly et al., 1997) is highly desirable because excess N input is one of the major reasons for water quality degradation such as Lake Eutrophication and Gulf Hypoxia.

Due to its robustness in representing SOC dynamics as influenced by agricultural management practices, the CENTURY soil organic matter (SOM)-residue model has seen its embracement by agro-ecosystem Models. For example, the Environmental Policy Integrated Climate (EPIC, Williams, 1995; Izaurralde et al., 2006) and Decision Support System for Agrotechnology Transfer (DSSAT, Jones et al., 2003; Gijsman et al., 2002) models have both incorporated concepts and equations from CENTURY for the simulation of coupled soil C and N dynamics. The CENTURY based EPIC SOM-residue model has been extensively tested for simulating SOC changes on cropland with various crop types and management practices (e.g. Izaurralde et al., 2006; He et al., 2006; Wang et al., 2005; Causarano et al., 2007, 2008, 2010; Apezteguía et al., 2009; Schwalm et al., 2010). The expanded capability of EPIC to simulate eroded and leached C losses (Izaurralde et al., 2007) is an important feature that enables connections between terrestrial and aquatic C processes. This strength of EPIC was emphasized in weighing candidate SOM-residue algorithms for SWAT, which has a well-established river network routing module addressing streamflow and fate of riverine pesticide and nutrients. In addition, the consistency between SWAT and EPIC in simulating terrestrial water cycling, crop growth and development, and soil erosion (Williams et al., 2008; Arnold et al., 2011) sorted out the EPIC SOM-residue model. As such, the major objective of this research was to incorporate the EPIC SOM-residue model into SWAT and evaluate its performance for assessing potential C sequestration/emission effects of different BMPs at a watershed scale. Although it was beyond the scope of this research to trace transport and fate of eroded and leached C in river networks, the new SWAT model is expected to pave a solid foundation for future research in this aspect. Given the apparent emphasis of this version of SWAT on Carbon, we refer to it as SWAT-C throughout the rest of this paper.

To fulfill the objective, we first provided a conceptual framework of the processes related to SOM-residue dynamics in soil. Next, we formulated a series of equations describing the addition, decomposition, transformation, and loss of SOM-residue through combining equations used in EPIC, CENTURY, and DSSAT. These equations were interfaced with the existing algorithms representing water cycling, nutrient cycling, plant growth, and soil erosion in SWAT, allowing for simulating impacts of crop rotation and management practices. We then used six agricultural sites from the AmeriFlux network (http://public.ornl.gov/ameriflux/) to evaluate SWAT-C in quantifying land–atmosphere C exchange. Daily eddy covariance (EC) and evapotranspiration (ET) observations of C flux or net ecosystem exchange (NEE) between land and atmosphere were used in the evaluation. At those sites with crop yield data, we also assessed SWAT-C in terms of predicting biomass growth, an important component of NEE. Finally, the performance of SWAT-C was discussed against other terrestrial carbon cycling models and literature reported eroded and leached SOC. Based on a literature review (https://www.card.iastate.edu/swat_articles/), this is the first study examining SWAT-C using EC observed daily water and C exchange between land and atmosphere. The test results obtained here are expected to provide valuable information on the reliability of the newly developed SWAT-C for simulating cropland C flux.

2. Methods and materials

2.1. Representation of the dynamics of SOM and residue

SWAT-C addresses addition, decomposition, transformation, and removal of each SOM-residue pool present in surface and subsurface soil layers (Fig. 1 adapted from Parton et al. (1994) and Izaurralde et al. (2006)). The number of soil layers and their depth are adjustable input parameters for SWAT, depending on soil properties at a specific site. Notably, the formation of slow and passive humus is highly associated with soil C stabilization, leading to the absence of slow and passive humus in surface layer (Parton et al., 1994; Gijsman et al., 2002). C and N produced during the decomposition of structural litter and microbial biomass at soil surface are added to slow humus in the first soil layer in CENTURY. We followed this scheme to jointly evolve SOM-residue at both soil surface and in the first soil layer. In SWAT and EPIC, the first soil layer is typically delineated with a 10-mm thickness, so as to better represent the rapid change of moisture, temperature, and nutrient at soil surface as influenced by weather conditions and human activities (e.g. precipitation, irrigation, and fertilizer application). Here, to be commensurate with the existing structure of SWAT, SWAT-C simultaneously addresses SOM-residue dynamics in both the surface and top 10-mm layers.