Environmental Modelling & Software 102 (2018) 39–48

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Simulating eroded soil organic carbon with the SWAT-C model

Xuesong Zhang [a, b, *]

[a] Joint Global Change Research Institute, Pacific Northwest National Laboratory, University of Maryland, College Park, MD, 20740, USA
[b] Earth System Sciences Interdisciplinary Center, University of Maryland, MD, 20740, USA

A R T I C L E I N F O

Article history:
Received 16 November 2017
Received in revised form
5 January 2018
Accepted 7 January 2018

Keywords:
Agriculture
Greenhouse gases
Erosion
Soil organic carbon

A B S T R A C T

The soil erosion and associated lateral movement of eroded carbon (C) have been identified as a possible mechanism explaining the elusive terrestrial C sink of ca. 1.7–2.6 PgC yr^{-1}. Here we evaluated the SWAT-C model for simulating long-term soil erosion and associated eroded C yields. Our method couples the CENTURY carbon cycling processes with a Modified Universal Soil Loss Equation (MUSLE) to estimate C losses associated with soil erosion. The results show that SWAT-C is able to simulate well long-term average eroded C yields, as well as correctly estimate the relative magnitude of eroded C yields by crop rotations. We also evaluated three methods of calculating C enrichment ratio in mobilized sediments, and found that errors associated with enrichment ratio estimation represent a significant uncertainty in SWAT-C simulations. Furthermore, we discussed limitations and future development directions for SWAT-C to advance C cycling modeling and assessment.

Software availability

Software: SWAT-C
Developer: Xuesong Zhang
Operating systems: Windows & Linux
Dependent software: FORTRAN 90
Availability: Free of charge; SWAT-C has been released at http://swat.tamu.edu/software/swat-executables within the latest version of SWAT. The new code revision regarding eroded C yields calculation and enrichment ratio estimation will be released to the public through the SWAT website.

1. Introduction

Accurate quantification of carbon (C) cycling in the Earth system is crucial for effective development of science-based decision tools and management strategies aimed at reducing C emissions. Current estimates of global CO_2 fluxes consistently infer a missing terrestrial C sink (also known as “residual terrestrial” or “land” sink) of 1.7 and 2.6 Pg C yr^{-1} for the 1980s and 1990s, respectively (IPCC, 2013). This residual sink is comparable in magnitude to other major components of the global C budget (e.g. the net ocean uptake of ca. 2.3 Pg C yr^{-1} or C emissions of ca. 1.0 Pg C yr^{-1} from land use change) (Ciais et al., 2014). A possible mechanism contributing to this missing sink is the soil erosion processes, which may induce a global C sink of ~0.12–1.5 PgC yr^{-1} (Smith et al., 2001; Stallard, 1998; Van Oost et al., 2007; Quinton et al., 2010). However, the C dynamics across terrestrial-aquatic interfaces, regulated by both biotic and abiotic processes across various temporal and spatial scales, remain poorly characterized. Given the magnitude and the degree of uncertainty associated with the erosion-induced C sink, there is an urgent need to elucidate its causes and mechanisms in order to avoid unexpected consequences when developing and deploying C management strategies and policies (Houghton, 2002).

Soil erosion and lateral movement of sediment and nutrients from land to waters not only modify soil quality but also alter terrestrial biogeochemical cycles (Lal, 2004; Liu et al., 2003; Berhe et al., 2007). Soil erosion laterally redistributes and removes soil organic carbon (SOC) and other nutrients across terrestrial landscapes. Global estimates of SOC erosion fluxes have varied widely from 0.5 to 6.0 Pg C yr^{-1} (Lal, 2003; Van Oost et al., 2007; Müller-Nedebock and Chaplot, 2015). Process-based terrestrial ecosystem modeling framework based on the CENTURY terrestrial C model (Parton et al., 1994) have been developed and tested for quantifying SOC erosion and associated biogeochemical processes (Harden et al., 1999; Liu et al., 2003; Izaurralde et al., 2007). Additionally, the soil erosion critically impacts trophic states as well as C stocks and flows in aquatic ecosystems (Cole et al., 2007; Tranvik et al.,

* Joint Global Change Research Institute, Pacific Northwest National Laboratory, University of Maryland, College Park, MD 20740, USA.
E-mail addresses: Xuesong.zhang@pnnl.gov, xzhang14@umd.edu.

https://doi.org/10.1016/j.envsoft.2018.01.005
1364-8152/

2009; Battin et al., 2009; Tank et al., 2010). Soil erosion mobilizes and introduces large amounts of particulate organic carbon (POC) from upland landscapes into streams, rivers, and reservoirs, where POC undergoes complex transport and transformation processes; POC not consumed in inland waters is transported by rivers to estuarine and coastal ecosystems (Hope et al., 1994), where it could be buried, biogeochemically transformed, or returned back to the atmosphere as CO_2 (Bauer and Bianchi, 2011). C transport and transformation processes link C cycling across terrestrial and aquatic ecosystems at the watershed scale and represent an important component of the boundless global C cycle (Battin et al., 2009), but has not been well understood and characterized (Trimmer et al., 2012).

Multiple field scale soil erosion models are available. The empirically-based Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978; Wischmeir, 1965) is a field scale model that is capable of simultaneously considering multiple soil erosion control factors, such as surface cover, terrain characteristics, precipitation, and conservation practices. Based on the USLE model, multiple revised methods have been proposed and widely adopted, such as Revised USLE (RUSLE) by Renard et al. (1991) and Modified USLE (MUSLE) by Williams and Berndt (1977). More physically based soil erosion models (Jetten et al., 1999; Nearing et al., 2005), such as Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), KINematic runoff and EROSion (KINEROS) (Woolhiser et al., 1990), EUROpean Soil Erosion Model (EUROSEM) (Morgan et al., 1998), and Plot Soil Erosion Model 2D (PSEM_2D) (Nord and Esteves, 2005), have been developed to explicitly represent detachment and transport processes during soil erosion (Ellison, 1947). Previous studies showed that field scale soil erosion modeling is subjective to multiple errors sources (Jetten et al., 1999; Nearing et al., 2005; Nord and Esteves, 2005), such as input data quality, user's choices in preparing input data, and inherent errors from simplified representation of the soil processes; often the importance of different uncertainty sources varies by models and experimental data employed. In general, the physically based models require more detailed spatial data and finer execution time step (e.g. minutes), and are often event based. A comparison of field scale soil erosion models (Jetten et al., 1999) showed that empirically models do not underperform physically models for long-term continuous simulations. Given the availability of terrain, climate and management data and the purpose of linking erosion with SOC losses for long-term simulations, we chose the MUSLE soil erosion model.

In addition, the MUSLE has been incorporated within the SWAT model (Arnold et al., 1998), which is a widely used process-based watershed model for reproducing observed hydrologic and/or pollutant loads across a wide range of watershed scales and environmental conditions, as well as for assessing impacts of conservation practices, land use, climate change, water management, and other scenarios (Gassman et al., 2007). Using MUSLE within the SWAT framework will greatly benefit future efforts to understand the fate of eroded sediments and C in downstream aquatic ecosystems and assess watershed scale C balance. Furthermore, in recognition of the need of a coupled watershed scale C cycling model, recent efforts (Yang and Zhang, 2016; Yang et al., 2017; Zhang et al., 2013b) enhanced and tested SWAT for simulating carbon dioxide (CO_2) and nitrous oxide (N_2O) fluxes of diverse upland ecosystems (referred to as SWAT-C hereafter). The revised coupled C, nitrogen and phosphorus cycles in SWAT-C are derived from three agroecosystem models, including the CENTURY model (Parton et al., 1994) and its daily version (DAYCENT) (Del Grosso et al., 2001), the Environmental Policy Integrated Climate (EPIC) model (Williams, 1990; Izaurralde et al., 2006), and the Decision Support System for Agrotechnology Transfer model (DSSAT) (Jones et al., 2003; Gijsman et al., 2002), as described in Zhang et al. (2013b). Wu et al. (2016) also explored the joint use of SWAT and DAYCENT to assess carbon dynamics. The SWAT-C model's C module has been tested for simulating CO_2 fluxes at 16 eddy covariance flux towers (Yang and Zhang, 2016; Zhang et al., 2013b). Those efforts lay a solid foundation for linking terrestrial C cycling with soil erosion.

Here, the major objective of this study is to test SWAT-C for simulating long-term sediment and eroded C using the long-term measurements from a small watershed (W118) in the North Appalachian Experimental Watershed (NAEW) research station (Hao et al., 2001). The outcome resulting from this study is expected to help understand the strength and weaknesses of SWAT-C for predicting the lateral movement of C from cropland into adjacent water bodies, thereby supporting its future development and applications to help understand C cycling across terrestrial and aquatic ecosystems.

2. Materials and methods

2.1. Description of the SWAT-C model

The SWAT model is a continuous, long term, distributed-parameter hydrologic model, which has been incorporated into the U.S. Environmental Protection Agency (US EPA) Better Assessment Science Integrating Point & Nonpoint Sources (BASINS) software package (Luzio et al., 2002), and is also being considered as a core watershed model by the United States Department of Agriculture (USDA) for applications in the Conservation Effects Assessment Project (CEAP) (Richardson et al., 2008) across watersheds in the U.S. For a watershed application, SWAT subdivides a watershed into subbasins connected by a stream network, and further delineates Hydrologic Response Units (HRUs) consisting of unique combinations of land cover and soils in each subbasin. For each HRU, SWAT simulates surface and subsurface flow, evapotranspiration, soil moisture sediment generation, carbon and nutrient cycling, and plant growth and development (Neitsch et al., 2011). The plant growth processes in SWAT are based on the EPIC model, which uses a revised version of Crop Environment REsource Synthesis (CERES) (Williams et al., 1989; Jones et al., 1991) and employs the concept of radiation-use efficiency by which a fraction of daily photosynthetically-active solar radiation is intercepted by the plant canopy and converted into plant biomass. Daily gains in plant biomass are affected by vapor pressure deficits, atmospheric CO_2 concentrations, nutrients availability, and other environmental controls and stresses.

In the SWAT-C version (Zhang et al., 2013b), following the CENTURY model (Parton et al., 1994), the soil organic matter (SOM) and residue are represented with five pools. Plant litter is divided into the easily decomposable metabolic (e.g. proteins and sugars) and recalcitrant structural (e.g. lignin and cell walls) component. An active microbial biomass pool that has a turnover of months to a few years, including soil microbes and microbial products. The slow humus pool receives C and N from the decomposition of structural litter, metabolic litter, and microbial biomass and often has a turnover time of 20–50 years. The most recalcitrant SOM lies in the passive humus pool, which includes physically and chemically stabilized SOM sorbed to clays with long turnover times (400–2000 years) (Parton et al., 1993, 1994). In addition to substrate specific properties, the decomposition and transformation of structural litter, metabolic litter, passive humus, slow humus, and microbial biomass are also influenced by abiotic factors, such as soil temperature, soil water content, tillage enhancement, oxygen availability, and soil texture (Parton et al., 1994; Gijsman et al., 2002; Izaurralde et al., 2006).

SWAT-C simulates soil erosion using the modified universal soil