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Evaluating carbon sequestration for conservation agriculture and tillage systems in Cambodia using the EPIC model

Kieu Ngoc Le[a,*], Manoj K. Jha[b], Manuel R. Reyes[c], Jaehak Jeong[d], Luca Doro[d], Philip W. Gassman[e], Lyda Hok[f], João Carlos de Moraes Sá[g], Stéphane Boulakia[h]

[a] Department of Energy & Environmental Systems, North Carolina A & T State University, Greensboro, NC, USA
[b] Civil, Architectural & Environmental Engineering, North Carolina A & T State University, Greensboro, NC, USA
[c] Sustainable Intensification Innovation Lab, Kansas State University, Manhattan, KS 66506, USA
[d] Texas A & M AgriLife Research, Temple, TX, USA
[e] Resource and Environmental Policy (REP) Division at CARD, Iowa State University, IA, USA
[f] Department of Soil Science, Faculty of Agronomy, Royal University of Agriculture, Phnom Penh, Cambodia
[g] Department of Soil Science and Agricultural Engineering, State University of Ponta Grossa, Av. Carlos Cavalcanti 4748, Campus de Uvaranas, 84030-900, Ponta Grossa, PR, Brazil
[h] Centre de Coopération Internationale en Recherche Agronomique pour le Dévelopment (CIDAD), UR AIDA/CSIS, Avenue Agroplois, 34398 Montpellier, France

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ABSTRACT

Soil organic carbon (SOC) sequestration was evaluated for several long-term rain-fed cropping systems for conservation agriculture (CA) and conservation tillage (CT) in Cambodia using the Environmental Policy Integrated Climate (EPIC) model. The mean crop yield, biomass and SOC stocks of four treatments and three replication in each primary cropping system (rice, soybean and cassava) were used for calibration and validation during the period 2009–2013. The CT and CA1 treatments were assigned to continuous cropping of primary crops. CA2 and CA3 treatments were assigned to rotated primary crops with maize. In all CA treatments, forage or legume cover crops were prior planted and intercropped with the primary crops to maintain full soil cover. The results show that EPIC successfully simulated crop yields, biomass, and SOC. However, the model tended to underestimate SOC in the CT treatments and overestimate SOC in the CA2 and CA3 treatments. Crop residue was found to highly influence SOC sequestration. Sediment loss in the CT treatments was found to be four times greater than CA treatments due to the CT tillage effects. The 20-year future simulations, using historical weather and automatically generated by EPIC, showed a decrease trend in SOC stocks in all CT treatments and an increase trend in most CA treatments, with the greatest increase for CA2 and CA3 treatments. Thus, the CA treatments in combination with the maize rotation were demonstrated to be more efficient to manage SOC sequestration over CA with one continuous primary crop.

1. Introduction

The term “carbon sequestration” is defined as the process of transferring CO_2 from the atmosphere into the soil in the form of long-lived pools of carbon (Andress, 2002; Goh, 2004; Olson et al., 2014; Yu et al., 2015). Meanwhile, SOC accumulation is the rate or the amount of SOC built up in the soil profile that can be quantified as a function of carbon inputs from crop residues, bulk density, protection by aggregates relative to clay and silt fraction, SOC concentration and thickness. Enhancement of soil organic carbon (SOC) sequestration is a viable climate change mitigation strategy by reducing CO_2 concentration in the atmosphere (West and Post, 2002; Lal et al., 2011; Gonzalez-Sanchez et al., 2012). In addition, increased SOC levels improves the productivity and sustainability of agricultural systems (Lal, 2004, 2006, 2015), reduces surface runoff and soil erosion (Lal, 2002; Söderström et al., 2014), and improves soil quality due to an increase in microbial activity (Feng et al., 2007; Sá et al., 2009; Sá and Lal, 2009; Wang et al., 2011). SOC sequestration is affected by many factors including C input, crop rotation, tillage management, climate condition, fertilization, and soil texture (Lal, 2004). Han et al. (2016) found that increased C input is the most efficient way to increase SOC sequestration. They also reported that climate condition is one of the key factors that drives SOC sequestration rate and accumulation. SOC sequestration is lowest in the tropics, followed by warm and cool temperate regions, regardless of

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[*] Corresponding author.
E-mail addresses: lngockieu@gmail.com (K.N. Le), mkjha@ncat.edu (M.K. Jha), mannyreyes@ksu.edu (M.R. Reyes), jeongj@tamu.edu (J. Jeong), ldoro@brc.tamus.edu (L. Doro), pwgassma@iastate.edu (P.W. Gassman), hoklyda@rua.edu.kh (L. Hok), jcmsa@uepg.br (J.C.d.M. Sá), stephane.boulakia@cirad.fr (S. Boulakia).

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different fertilization methods that rely on balanced chemical fertilizers, chemical fertilizers with straws, and chemical fertilizers with manure (Han et al., 2016). In addition, the amount of SOC accumulation in the tropics is less than in temperate regions. However, the rate of SOC change is greater in the tropics, thus leading to a shorter time for SOC equilibrium to be attained in tropical regions (Han et al., 2016). On the other hand, Lal (2004) stated that SOC loss is higher in the tropics than in the temperate regions due to severe soil depletion and degradation, and low crop productivity. Tropical soils can lose up to 50 to 67% of initial SOC within five years versus 50 years in the temperate regions (Lal, 2003).

Cambodia is a developing and agricultural-based country where some 80% of the population is involved directly or indirectly in agriculture (Prasad, 2016). The country is suffering C loss due to poorly managed conversion of natural forest into croplands (Belfield et al., 2013). Continuous soil cultivation combined with rainfall intensity causes tremendous soil loss. The U.S. and other developed countries have invested significant funding and efforts to help Cambodian farmers develop technology for a more sustainable agriculture, including conservation agriculture (CA) and conservation tillage (CT) practices, which can increase crop productivity and protect natural resources (Prasad, 2016; USEPP, 2016). CA and CT practices are being promoted to reduce runoff, increase SOC, and create sustainably intensified agriculture production systems. CA is defined on the basis of three principles (FAO, 2015) referred to as the McD principles: M − Minimum soil disturbance, C − continuous ground cover, and D − Diversified crop rotations or mixed. Lal (2015) adds integrated nutrient management as the fourth principle of CA, and emphasizes that CA mimics the natural system, creates positive soil budgets, strengthens nutrient cycling, and reduces emission of greenhouse gasses. CA has become increasingly popular due to multiple benefits including improved production efficiency and soil productivity, protection of soil, robust sustainable agriculture and climate change mitigation (Gonzalez-Sanchez et al., 2012; Palm et al., 2014; Busari et al., 2015). CA increases soil infiltration rate and soil water content (Thierfelder and Wall, 2009). CA was found to increase the amount and biomass of all soil organisms including microbes, macrofauna and nematofauna, but not the predaceous nematodes (Henneron et al., 2015). Dusserre et al. (2017) reported that CA reduced blast disease in upland rice compared to conventional tillage (CVT). CA has been shown to increase SOC and residual water content in upland crop production systems in northern Mindanao in the Philippines (Ella et al., 2016). Besides CA, CT is also believed to have great potential to increase SOC sequestration (Olson et al., 2014). CT in this study is defined as disc-tilled from 15 to 20 cm depth that leaves all crop residue on the soil surface after harvesting and before planting. CT practices were found to improve physicochemical and microbiological soil properties (Mathew et al., 2012); increase soil respiration, microbial biomass and fungal abundances (García-Orenes et al., 2013); decrease bulk density and increase SOC, microbial biomass carbon and dehydrogenase activities (Das et al., 2014); and increase macro-fauna diversity and abundance (Mutema et al., 2013). A sizeable number of agronomic studies found that cropping systems with combined CA and CT sequestered a significant amount of SOC (Boulakia et al., 2012; Corsi et al., 2012; Sá et al., 2014; Hok et al., 2015; Ella et al., 2016). Meanwhile, farmers tend to rotate between CT and CVT after two to three years implementing CT (Kurkalova and Tran, 2017), especially those farmers who rotated soybean with maize (Tran and Kurkalova, 2016). Farmers also adopted tillage practices based on soil erodibility and market price (Tran and Kurkalova, 2016).

There is continuing debate as to whether CA can sequester more SOC than CVT or CT. Baker et al. (2007) believed that sampling protocol might bias the results. Most of the reviewed studies which showed that CT sequestered more SOC were based on sampling depths of only 30 cm. Studies that reported sampling to deeper depths did not consistently show similar rates of SOC increase under CT; in fact, higher SOC concentrations were found in soil surface layers in response to CT treatments versus higher SOC levels in deeper layers under CVT (Baker et al., 2007). Hok et al. (2015) conducted SOC research in Cambodia for contrasting tillage that they called no-till (NT) and CVT treatments but the treatments were actually CA and CT, respectively, by definition. Hok et al. (2015) also found higher SOC stock levels for CA treatments versus CT treatments in the top 0–5 cm depth, but no significant differences among the CT and CA treatments was found in the sub-soil layers up to 100 cm deep for rice, soybean, and cassava cropping systems. However, the amount of surface soil loss from each system was not taken into account in their soil sampling process. SOC stocks were found to decrease in the CVT system at a depth of 0–20 cm but to increase in response to NT, with more SOC loss for tropical conditions versus subtropical conditions for CVT for two respective sites located in subtropical and tropical Brazil that are characterized by Oxisols (clay) soils (Sá et al., 2013). Powlson et al. (2016) conducted a meta-analysis of SOC stock changes in the Indo-Gangetic Plains (IGP) and sub-Saharan Africa (SSA) tropical regions and found that SOC increased 0.16–0.49 Mg ha^{-1} yr^{-1} in the IGP and 0.28–0.96 Mg ha^{-1} yr^{-1} in the SSA under CA compared to CVT practices. However, the authors stated that in most of the reviewed studies, the increase in SOC among the CA and CT treatments were not significantly different but there were significant differences between CA and CVT practices (Powlson et al., 2016). Paudel et al. (2014) observed a significant increase in SOC under CA compared to CVT in the upper 0–20 cm depth but not in the 20–40 cm depth for a sandy loam soil in Nepal, after a five-year crop rotation that included rice and wheat. The ecosystem benefits of CA and CT are clear even though CA does not consistently improve SOC. Thus, there is still a need to understand SOC dynamics in CA and potential approaches to CA that could enhance SOC sequestration.

Two of the most common approaches to studying carbon sequestration are long-term field experiments and modeling (Lugato et al., 2015). The former approach is often time-consuming and costly compared to the modeling approach. When long-term SOC observation is limited, simulation of SOC cycling and sequestration based on available observed data is strongly needed (Han et al., 2016). An ideal modeling approach is to interface a process-based model with experimental data including crop rotations and management practices (Izaurralde et al., 2006). The field scale CENTURY (Parton et al., 1988, 1993) and the Environmental Policy Integrated Climate (EPIC) (Williams et al., 1989) models are the two most widely used process-based models for simulating soil carbon sequestration (Gassman et al., 2005; Causarano et al., 2008; Abrahamson et al., 2009; Billen et al., 2009; Tornquist et al., 2009; Viaud et al., 2010; Izaurralde et al., 2012; Stockmann et al., 2013; Arunrat et al., 2014). In this study, EPIC was chosen because it is one of the few models that can simulate the interaction of soil, water, plant nutrient uptake, and SOC cycle for the complete ecological system including intercropping of up to 12 separate crops.

EPIC was developed to simulate plant and soil ecological systems including the processes of weather, crop growth, crop and soil management, tillage, soil temperature, carbon cycling, nutrient cycling (N, P, K), soil erosion, hydrology, and soil water dynamics (Williams et al., 1984, 1989; Williams, 1985; Williams and Singh, 1995; Izaurralde et al., 2006, 2012). The current coupled carbon and nitrogen cycling routine used in EPIC was adapted from the CENTURY model, and the routine was further modified by incorporating a C:N ratio to simulate SOC cycling at an ecosystem scale (Izaurralde et al., 2006). In the modified EPIC, C and N transform between litter and soil organic matter (SOM) across the soil profile in five pools: metabolic litter, structural litter, active humus, slow humus, and passive humus (Izaurralde et al., 2006, 2007). The surface litter fraction includes a slow humus pool as an addition to the metabolic and structural litter pools in the CENTURY model. The pools vary in size and function, and their turnover time can be days to hundreds of years. Metabolic and structural litter, based on N and lignin contents, are composed of organic materials such as plant residues, roots, and manures. Plant lignin concentration is simulated as