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Crop and soil organic matter simulation models – A brief review of their basic features and application in sub-Saharan Africa

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Introduction

Over the past decades, numerous crop-soil models have been developed to represent dynamic processes in cropland systems, including soil organic carbon (SOC) dynamics (Campbell and Paustian, 2015). These models use mathematical equations that determine carbon allocation in the vegetation and biomass and soils to represent biogeochemical processes, such as photosynthesis, respiration and decomposition. Furthermore, a range of crop management practices are represented in most of the models, enabling an assessment of their impacts on SOC in agricultural systems. Although models were initially developed for research purposes, they are increasingly becoming important in many aspects of environmental policies (Manlay et al., 2007). Extensively tested models provide effective tools that can be used in identifying sustainable land management practices across different agro-ecological conditions. Compared to field experiments, which are time and resource consuming, models are more effective for making predictions and understanding crop and SOC dynamics on large scales and different time scales.

However, the choice of the model depends on the ability of the model to simulate key processes in the region of interest. We conducted a survey to identify the features of the commonly used crop-soil models in order to inform the choices for application in sub-Saharan Africa. The survey was administered online to the model developers. In addition, we also conducted a literature search to assess the usage of the different models in different parts of sub-Saharan. In this brief, we provide a basic summary of the information from the survey and literature review.

Summary of the basic features

The models considered for the survey included point and landscape level that have been applied in different in regions in the globe for simulating crop and soil organic carbon dynamics. The 9 models that participated in the survey are: DayCent/Century, RothC, DNDC, DAISY, MONICA, CropSyst, APSIM, DSSAT, and STICS. Below a brief description of each of the models.

i. **DayCent** is a biogeochemical model that simulates crop growth, SOC dynamics, carbon and trace gas fluxes in croplands as well as forests, grasslands, and savannah ecosystems (Del Grosso et al., 2002; Parton et al., 1998). It is the daily time step version of the Century model. The model allows for an assessment of a wide range of agronomic management practices (e.g., tillage, fertilization, irrigation, crop harvest and manure addition).

ii. **MONICA** is the latest generation of HERMES (Kersebaum, 1995, 2007) model versions that simulates crop growth, water and nitrogen uptake, and the SOC dynamics in the soil (Nendel et al., 2011).

iii. **DAISY** is a mechanistic model that represents physical and biological processes in agricultural fields (Hansen, 2002). It simulates water, energy, carbon and nitrogen cycles in the vegetation and soils agricultural systems.

iv. **RothC** is a model for turnover of carbon in non-water-logged topsoil (Coleman, 2014). It allows for the assessment of the effects of soil type, temperature, soil moisture and plant cover on the turnover processes. The model does not represent crop growth and is hence not used in modelling crop dynamics.

v. **STICS** simulates plant growth, water, carbon and nitrogen fluxes in annual crops, perennial grasses or trees (Brisson et al., 2003, 1998).

vi. **DSSAT** (Decision Support System for Agrotechnology Transfer) is a software application program that comprises crop simulation models for over 42 crops, which simulate growth, development and yield as a function of the soil-plant-atmosphere dynamics. DSSAT simulates water, nitrogen and carbon cycles for these crops, and can be used to assess the effects of climate change impacts and different management decisions (Jones et al., 2003).

vii. **CropSyst** is a cropping systems simulation model developed as an analytical tool to study the effects of climate, soils, and management on cropping systems productivity and the environment (Stöckle et al., 2003).

viii. **APSIM** is a comprehensive model developed to simulate biophysical to simulate biophysical processes in agricultural systems. APSIM includes modules that simulate soil processes including water balance, N and P transformations, soil pH, erosion and a full range of management controls in diverse range of crops (Keating et al., 2003).

ix. **DNDC** simulates C and N in agro-ecosystems and predicts crop growth, SOC dynamics and N leaching and trace gases emissions (Li et al., 2012).

Table 1 provides a summary of the features of the model including, the time step, number of layers and carbon pools, the extent of application and the simulated nutrients and greenhouse gases. The responses show that most of the models can simulate both crop and soil organic carbon (SOC) dynamics, with the exception of RothC which simulates only SOC dynamics. Apart from RothC, all the reviewed models include a layered soil profile to represent water dynamics in the soil. Most of the models use a tipping bucket approach for simulating soil hydrologic cycle and water redistribution, with the exception of CropSyst and Daisy that use the Richard's equation. Although the tipping bucket model has been shown to work well in representing soil water holding properties, it has less accuracy in estimating soil moisture distribution in the soil profile (Shelia et al., 2018). Majority of the models can simulate CO_2 and N_20 fluxes with a few also simulating CH_4 fluxes. Apart from RothC, all the SOM dynamics are able to simulate the most common agronomic management practices (i.e. tillage, fertilization, manuring, and crop rotation) (Table 2).

More details on the representation of soil, plant ecophysiology, management and greenhouse gases and their weaknesses can be found in Brilli et al., 2017.

Table 1: Overview of the basic features of the surveyed models

	DayCent	RothC	DNDC	DSSAT	CropSyst	MONICA	STICS	Daisy	APSIM
Scope	Crop and SOC modeling	SOC modeling	Crop and SOC modeling	Crop and SOC modeling	Crop and SOC modeling	Crop and SOC modeling	Crop and SOC modeling	Crop and SOC modeling	Crop and SOC modeling
Timestep	Daily	Monthly	Daily	Daily	Daily	Daily	Daily	Hourly	Daily
Extent of application	Point-scale, regional and global	Point-scale, regional and global	Point-scale and regional	Point-scale, regional and global	Point-scale and regional	Point-scale and regional	Point-scale	Point-scale	Point-scale, regional and global
No. of SOC pools	3	5	4	3	3	3	2	3	3
Name of pools	Active, Slow, passive	Decomposable Plant Material (DPM), Resistant Plant Material (RPM), Microbial Biomass (BIO) and Humified Organic Matter (HUM)	Litter, microbes, Humads, Passive	Active, Slow, Passive	Active, Passive, Slow	Added Organic Matter (AOM), Soil Microbial Bio-mass (SMB), Native Soil Organic Matter (SOM)	Active and Inactive fractions	Added organic matter (AOM), Soil Microbial Biomass (SMB), and Native Soil Organic Matters (SOM)	Microbial biomass (BIOM), Humus (HUM), Inert organic matter (IOM)
Layered profile	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maximum no. of soil layers	14	1	Variable across soils	20	17	20	5	User specified	6
Maximum depth of SOC simulation	20 cm	30 cm	User specified	All layers	All layers	40 cm	User specified	User specified	User specified
Equation governing decomposi-tion	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics	1st order kinetics
Soil water redistribu-tion equation	Tipping bucket	Tipping bucket	Tipping bucket	Tipping bucket	Richard's equation	Tipping bucket	Tipping bucket	Richard's equation	Tipping bucket and Richard's equation
Water erosion module	No	No	Yes	Yes	Yes	No	Yes	No	Yes
Simulated gas fluxes	CO_2, N_20, CH_4	CO_2	CO_2, N_20	CO_2, N_20	CO_2, N_20	CO_2, N_20	CO_2, N_20	CO_2, N_20	CO_2, N_20
Simulates soil nutrients	Nitrogen, Phosphorous, Sulphur	Carbon	Nitrogen, Phosphorous,	Nitrogen, Phosphorous,	Nitrogen	Nitrogen, Sulphur	Nitrogen	Nitrogen	Nitrogen and Phosphorous
Mulch layer affects water dynamics and heat balance in soil	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 2: Overview of the crop management practices included the in surveyed models

Management	DayCent	RothC	DNDC	DSSAT	CropSyst	MONICA	STICS	DAISY	APSIM
Crop harvest	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tillage	✓	✗	✓	✓	✓	✓	✓	✓	✓
Fertilization	✓	✗	✓	✓	✓	✓	✓	✓	✓
Irrigation	✓	✗	✓	✓	✓	✓	✓	✓	✓
Manuring	✓	✓	✓	✓	✓	✓	✓	✓	✓
Crop rotation	✓	✗	✓	✓	✓	✓	✓	✓	✓
Intercropping	✗	✗	✓	✓	✗	✗	✓	✓	✓
Agroforestry	✗	✗	✗	✗	✗	✗	✗	✗	✓
Cover cropping	✓	✗	✓	✓	✓	✓	✓	✓	✓
Pesticides application	✗	✗	✗	✗	✗	✗	✗	✓	✗

Application of the models in sub-Saharan Africa

Published modelling studies in sub-Saharan Africa were reviewed to assess the type of studies crops, purpose of the study and the applied models. The review indicates that APSIM and DSSAT are the most widely used crop-soil mods in SSA with most of the studies being in West and Southern Africa region and only a few studies in East Africa (Table 3). Majority of the APSIM and DSSAT studies focussed mainly of crop production (i.e. yield) and a lot of emphasis has also laid on assessing and quantifying the impacts of climate change and management on yields. There are a few studies on SOC, but the key focus has been on model evaluation. While agronomic management impacts on SOC are widely studied in other regions in the globe, there are only a few studies within SSA. Out of the 40 reviewed studies, majority were on point-scale modeling with only 2 being on a landscape level.

Table 3: A summary of the reviewed modeling studies in sub-Saharan Africa including the model, country/region of study, purpose of study and the reference.

MODEL	COUNTRY/ REGION	CROP	PURPOSE OF STUDY	REFERENCE
Century	Sudan	Millet and sorghum	Estimating SOC in different land use including cropland	Ardö and Olsson, 2003
Century	South Africa	Sugarcane	Validation, calibration and predicting SOC in sugarcane systems under different management	Galvados et al 2009
Century and RothC	Nigeria and Sudan	Millet and groundnuts	Assessing the effects of improved agricultural management practices on SOC	Farage et al., 2007
Century and RothC	Kenya	Maize and maize-bean rotation	Model evaluation using long-term experiments	Kamoni et al., 2007
RothC	Niger	Millet	Validation of SOC dynamics using long-term experiments	Nakamura et al., 2011
DSSAT	Ghana	Maize and groundnuts	Economic analysis on management practices that enhance SOC sequestration	González-Estrada et al., 2008

MODEL	COUNTRY/ REGION	CROP	PURPOSE OF STUDY	REFERENCE
DSSAT	Kenya and Uganda	Maize and maize-bean rotation	Validation of DSSAT using two long-term experiments and projection of SOC changes	Musinguzi et al., 2014
DSSAT	Burkina Faso	Cotton, sorghum, peanut and maize	Model evaluation with SOC and yields using long-term experiment data	Soler et al., 2011
DSSAT	Cote d'Ivoire	Maize	Assessing the impacts of conservation agriculture on yields	Worou et al., 2019
DSSAT	Niger	Maize	Assessing the contribution of weather, crop and soil to uncertainties in simulated yields	Jones et al 2012
DSSAT	Ghana	Maize	Calibrating and validating simulated grain and biomass yields in the model	McCarthy et al 2012
APSIM	Malawi	Maize and maize double legume intercrops	Model calibration, validation and assessing the sustainability of double-legume rotations	Smith et al., 2016
APSIM	Ghana	Sorghum	Modelling the impacts of nutrient and residue management on yield and SOC	MacCarthy et al., 2009
APSIM	Eastern and Southern Africa - Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbambe	Maize	Charactering maize production in different climate conditions	Seyoum et al., 2017
APSIM	Kenya	Maize/ Agroforestry systems	Simulating the impacts of shading on maize	Dilla et al., 2018
APSIM	Nigeria	Maize	Evaluation of APSIM using yield data from different maize cultivars	Yamusa and Akinseye, 2018
APSIM	Ghana	Maize	Assessing the impacts of climate change and climate variability on maize yields	Fosu-Mensah et al., 2019
APSIM	Malawi	Maize and maize-pigeon pea	Model evaluation and assessing the impacts of climate change on yields	Ollengburger Mary 2012iversity
APSIM	Ethiopia	Sorghum	Assessing impacts of climate change and climate variability on production	Gebrekiros and Araya, 2015
APSIM	Ghana	Maize	Assessing the effects of seasonal climate variability on efficiency of mineral fertilizer	MacCarthy et al., 2015
APSIM	Tanzania	Maize	Assessing the impacts of improved management practices on maize yields under current and future climate	Tumbo et al., 2012
APSIM	Eastern and Southern Africa - Ethiopia, Kenya, Tanzania, Malawi, Mozambique and Zimbambe	Sorghum	Assessing the impacts of increased temperatures on sorghum yields	Turner and Rao, 2013

MODEL	COUNTRY/ REGION	CROP	PURPOSE OF STUDY	REFERENCE
APSIM	West Africa	Sorghum	Assessing the impacts of climate change on yields	Sultan et al., 2014
APSIM	West Africa	Sorghum	Assessing the options for climate change adaptation	Guan et al., 2017
APSIM	Southern Africa	Sorghum	Quantifying the response of maize yield to projected climate change and key management practices (i.e. planting date, cultivar, fertilizer use)	Rurinda et al., 2015
APSIM	Zimbabwe	Maize	Model calibration and simulating yield response to reduced tillage and mulching	Mupangwa et al., 2011
APSIM	Niger	Millet	Assessing impacts of nitrogen management on yields	Akponikpè et al., 2010
APSIM	South Africa	Maize	Assessing impacts of no-till on water fluxes and maize productivity	Mupangwa and Jewitt, 2011
APSIM	Kenya	Maize	Evaluation of the model with data on nitrogen and residue man-agement	Kisaka et al., 2016
APSIM	South Africa	Sorghum-cowpea intercrop	Evaluation of growth, yield and crop water use	Chimonyo et al., 2016
APSIM	Zimbabwe	Maize	Model calibration for maize yield and N mineralization and simulat-ing the effects of tillage, fertilization management and planting dates on yields and N mineralization	Masvaya et al., 2018
APSIM	Zimbabwe	Maize-Mucuna rotation	Comparing conventional farmer practices with improved practices comprising of manure application and rotations with cover crop (i.e. Mucuna)	Masikati et al., 2014
APSIM	Ghana	Maize	Simulating the long term influence of nitrogen and phosphorous on maize yield	Fosu-Mensah et al., 2012
APSIM	Malawi	Maize	Assessing the effective use of nitrogen and phosphorous with rainfall variations	Kamanga et al., 2014
DSSAT and APSIM	Southern Ethiopia	Maize	Assessing maize growth and yield under present and future climate	Araya et al., 2015
DSSAT and APSIM	West Africa	Sorghum	Assessing the performance of the models in simulating sorghum germplasm in different climate and soil conditions	Akinseye et al 2014
CropSyst	Burkina Faso	Millet	Simulating yields across different climatic conditions	Badini et al., 1997
CropSyst	Cameroon	Maize, sorghum, groundnut, and soybean	Yield validation	Tingem et al., 2009
CropSyst	Kenya	Maize and Maize-Tephrosia rotation	Simulating nitrogen dynamics and nitrous oxide emissions in a long-term trial under integrated soil fertility management	Sommer et al., 2016
STICS	Mali	Sorghum	Simulating crop developments	Folliard et al., 2004

Conclusion

The objective of this research brief was to summarize the main features of some of the most widely used crop models and assess their application in sub-Saharan Africa (SSA). The conducted survey indicates that most models can simulate crop growth and SOC dynamics with the exception of RothC, which simulates on SOC dynamics. Except for agroforestry and intercropping, the other common agronomic management practices are well represented in most of the models. Out of the 9 surveyed models, APSIM and DSSAT are the most widely used in the region. For SOC, the emphasis has been on calibrating and validating the models with only a few study with model application in understanding the drivers of SOC dynamics and the impacts of agronomic management practices. Although this review may not be exhaustive, it shows that despite the use of models gaining momentum in SSA the focus has been on point-scale modelling. Furthermore, modelling studies in the East Africa region still remain scarce compared to West and Southern Africa. While model evaluation is critical in identifying their strength and weaknesses, an application of the model at wider scales would increase their application in informing policies within their region. This study shows that models are still underutilized especially for assessing and quantifying the drivers of crop and SOC dynamics at wider scales in SSA.

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