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Conservation agriculture with drip irrigation: Effects on soil quality and crop yield in sub-Saharan Africa

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Abstract: The traditional agriculture production system in sub-Saharan Africa (SSA) caused significant soil erosion and degradation of soil quality. In addition, dependability of rainfall for irrigation needs limits the crop production. Advanced agricultural practices are thus needed at the local level to sustain the livelihood of smallholder farmers in the region. In this study, conservation agriculture (CA) practice with drip irrigation technology was compared (using field experiments and watershed modeling) with the traditional conventional tillage (CT) practice for its potential in improving soil quality and crop productivity in the region. Biophysical data were collected (2015 to 2017) from a total of 43 paired plots (CA and CT) at four study sites in SSA: Dangishita and Robit in Ethiopia, Yemu in Ghana, and Mkindo in Tanzania. The Agricultural Policy/Environmental eXtender (APEX) model was calibrated and validated with reasonable efficiency in simulating crop yields for both CA and CT practices; average PBIAS ≤±12% and ≤±11%, for CA and CT. The impact of the CA system on soil quality (soil carbon [C] and nitrogen [N]) was analyzed based on the well-tested model prediction results. The total C and N were increased under CA across the study sites on average by 6% and 4.1%, when compared to CT over the study period. Both the experiment and model prediction showed that crop yield was significantly improved by CA—on average 37.4% increases across the sites when compared to CT. Conservation agriculture with drip irrigation was an efficient local strategy to improve crop production in the region while enhancing the ecosystem.

Key words: Agricultural Policy/Environmental eXtender (APEX) model—conservation agriculture—crop yield—drip irrigation—soil quality

The ever-increasing population in sub-Saharan Africa (SSA) depends on subsistence agriculture because of various constraints (Admassie 2002; Shiferaw et al. 2014). Soil degradation is one of the main causes for the decline of crop productivity and food crises in the region (Palm et al. 2010; Tully et al. 2015). Some factors that contribute to soil degradation are rapid population growth, lack of proper soil and water management strategies, and deforestation (Blanco and Lal 2010; Worqlul et al. 2017). The commonly used agricultural practice in SSA is traditional tillage, which contributes significantly to soil degradation. In addition, the expansion of agricultural land at the cost of the forest is another challenge that leads to soil degradation (Bekunda et al. 2010; Dile et al. 2013). Therefore, transforming the current agricultural practices to a modern agriculture system is critical in sustaining production and the ecosystem in this region simultaneously.

Conservation Agriculture Production System (CAPS) is defined using three basic principles: minimum soil disturbance with no-till practice, continuous organic mulch cover, and diverse cropping (Friedrich et al. 2012). CAPS is the essential foundation of the "Save and Grow" agriculture paradigm of the Food and Agricultural Organization of the United Nations (FAO 2011) that replaces the Green Revolution of the 1960s (Duvick and Cassman 1999). In the "Save and Grow" system, agriculture must enhance the ecosystem while growing crops. One benefit provided by CAPS is that it has the potential to restore and enhance the soil ecosystem and sustain agricultural productivity (Kimble et al. 2002; Le et al. 2018; Reeves 1997). The improvement of soil organic carbon (C) and nitrogen (N) is considered an indicator of the improvement of soil quality (Drinkwater et al. 1998; Lal 2015; Le et al. 2018; Reeves 1997). Soil nutrients are limiting factors for crop growth in tropical regions (Subbian et al. 2000), which is solely dependent on soil organic C (Reeves 1997). An increase in soil organic C improves crop yields by increasing not only nutrient supply but also available water capacity and soil structure (Lal 2006). Thus, CAPS plays an important role in sustaining and advancing food security (Dile et al. 2013; Hobbs et al. 2008; Le 2017; Wall 2007), while minimizing negative effects on the environment (Wang et al. 2011b).

The rainfed agricultural production in SSA is adversely affected becuase of high rainfall variability (Ericksen et al. 2013; Kotir 2011; Schlenker and Lobell 2010; Shiferaw et al. 2014). Irrigation can help to minimize the adverse effect of rainfall and maximize productivity in the region by enabling year-round cropping (Awulachew et al. 2008; Worqlul et al. 2018b). However, only a small portion of agricultural land is currently under irrigation in the region using conventional practices. The efficiency of water application technology needs to be critically considered as water scarcity is a major constraint in the region (Ashton and Turton 2009; Hanjra et al. 2009; Ngigi 2009). Efficient water application techniques have the potential to maximize irrigation efficiency and crop yields. Recent evidence indicated that drip irrigation is capable of providing the highest

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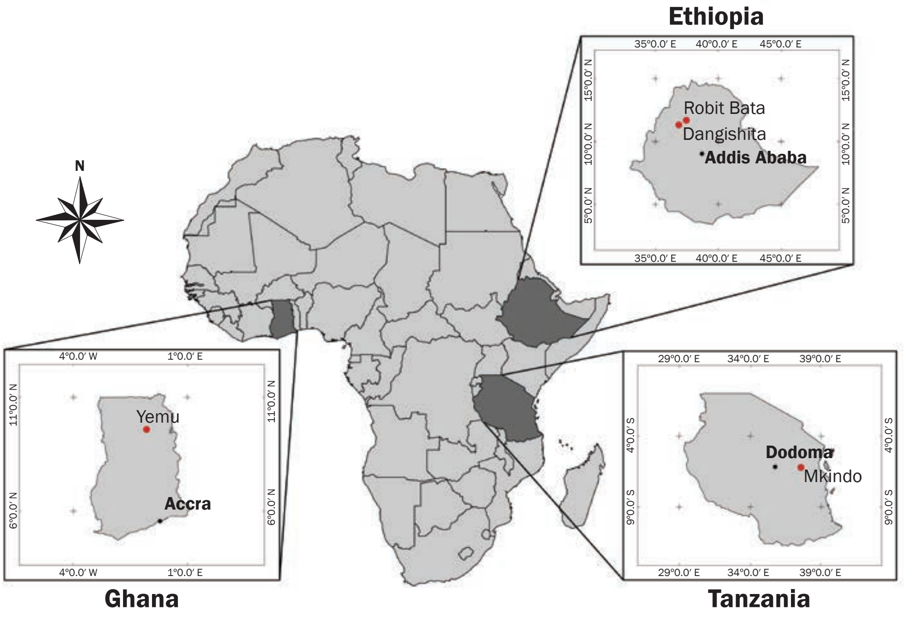
water use efficiency (Jha et al. 2016), and the combination of CAPS with drip irrigation technology together provides more efficient soil and water management techniques and has essential contributions to sustain the ecosystem and advance food production.

Watershed and land management models have been used frequently to evaluate the effects of various management practices on crop yield and soil quality (Wang et al. 2008), and modeling techniques coupled with a field experiment can provide a comprehensive assessment of the effects of CAPS with drip irrigation. However, it is essential to adjust the models for the region of interest through model parameter calibration using data obtained from field-scale experiments to generate reliable evidence. A well-tested watershed model for a specific region can help to manage agricultural systems (Gaydon 2014), and the Agricultural Policy/Environmental eXtender (APEX) model is among the few efficiently tested models in evaluating field management practices (Gassman et al. 2010a; Moriasi et al. 2012; Van Liew et al. 2017; Wang et al. 2011a; Zhang et al. 2016).

Figure 1

Locations of study sites in sub-Saharan Africa.



Several studies were conducted in the region to evaluate the effects of conservation agriculture (CA) principles on various environmental variables (Ahmad et al. 2007; Andersson and D'Souza 2014; Arslan et al. 2014; Baudron et al. 2015; Brouder and Gomez-Macpherson 2014; Corbeels et al. 2014; Dalton et al. 2014; Gathala et al. 2011; Nyamangara et al. 2014). However, previous studies were limited to grain crops and mainly rainfed systems. There are limited quantitative studies in the region to investigate the effects of CAPS on soil quality in vegetable production. The effects of CAPS on crops vary depending on several factors, including climatic condition, agricultural inputs (e.g., water, fertilizers, and pesticides), soil characteristics, temperature, vegetative cover, and cropping season. For instance, Qin et al. (2015) found a higher positive effect of CAPS on crops from less water input, increased fertilizer, and higher temperature. Grain production in the region is mostly rainfed (cold season) whereas vegetables are mostly produced in the dry (hot) season with irrigation. Less water input with irrigation to vegetables and relatively high water input to grains from rainfall will have an effect in conserving soil nutrients and hence improving crop yield. Grains are closely grown crops whereas vegetables have space (i.e., vegetative cover is different), indicating relatively higher positive effects of CAPS in vegetables in cooling soil temperature and reducing soil evaporation. This study combined a field experiment with APEX modeling to investigate the impact of CAPS with drip irrigation in home vegetable gardens on soil quality (C and N) and the consequent improvement in yield. Paired field sites were established for CA and conventional tillage (CT) practices, and biophysical data were collected for a network of 43 plots at various locations in Ethiopia, Ghana, and Tanzania. The study results are most useful for demonstrating the usefulness of CA with drip irrigation for improving soil quality and crop yield in the region.

Materials and Methods

Site Description. Biophysical data were collected from four study sites in SSA for the APEX model parametrization (figure 1). "Biophysical data" refers to the measurement of physical changes over time. Soil characteristics, surface runoff, land preparation, crop growth (planting to harvest), mulching, irrigation and rainfall, fertilizer and pesticide, and crop yield were the biophysical data collected in and around the study sites. The study sites were Dangishita and Robit (northwestern part of Ethiopia), Yemu (northern region of Ghana), and Mkindo (eastern part of Tanzania). The experimental setup was realized for a total of 43 paired plots of 100 m^2 in size, where 50 m^2 was for CA and another 50 m^2 for CT practice. In CA plots, dried grass mulch was used in combination with no-till practice. In CT plots, the farmers' traditional tillage practice of using hand tools without mulching the soil was employed. The plots were randomly assigned to CA and CT management, and drip irrigation was installed on both CA and CT management. The soil types in the study sites range from hydrologic group A (high infiltration and low runoff generating potential) to D (low infiltration and high runoff generating potential). Dangishita and Robit sites have Chromic Luvisols (hydrologic group C), which has 51% sand and 27% clay. Yemu and Mkindo sites have Ferric Luvisols (hydrologic group A) and Ferallic Cambisols (hydrologic group D), respectively. Ferric Luvisols have 79% sand and 10% clay texture whereas Ferallic Cambisols have 48% sand and 44% clay texture (table 1).

Various crops were grown for this study for a period of two to three years in Ethiopia (2015 through 2017), Ghana (2016 through 2017), and Tanzania (2016 through 2017). Crops grown in Ethiopia include garlic (*Allium sativum* L.), onion (*Allium cepa* L.), tomato (*Solanum lycopersicum* L.), and cannonball cabbage (*Brassica oleracea* L.) whereas crops grown in Ghana include sweet potato (*Ipomoea batatas* [L.] Lam.), cucumber (*Cucums sativus* L.), and green pepper (*Capsicum annuum* L.). Cucumber yields in

Table 1
Soil characteristics in the study sites (Assefa et al. 2018).

	Chromic Luvisols		Ferric Luvisols		Ferallic Cambisols	
Soil characteristics	**Layer 1***	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
Texture class†	Sandy clay loam	Sandy clay loam	Sandy loam	Sandy clay loam	Sandy clay loam	Clay loam
Wilting point (% volume)†	16.80	20.60	6.40	13.40	24.50	26.50
Field capacity (% volume)†	27.90	32.30	12.60	21.30	35.70	37.80
Soil water (cm cm^{-1})†	0.11	0.12	0.06	0.08	0.13	0.11
Saturated hydraulic conductivity (mm h^{-1})†	6.81	2.68	55.15	13.73	1.71	0.51
Bulk density (g cm^{-3})†	1.54	1.52	1.56	1.61	1.47	1.49
Sand (%)	51	45	79	68	51	48
Silt (%)	22	21	11	10	10	8
Clay (%)	27	34	10	22	39	44
Organic carbon (% weight)	0.63	0.35	0.53	0.30	1.73	0.78
Hydrologic soil group	C		A		D	

*Layer 1 refers to topsoil (up to 30 cm from the surface), and layer 2 refers to the soil from 30 cm to 100 cm.

†Soil characteristics determined using the soil-plant-atmosphere-water field and pond hydrology program.

Yemu were very small because of diseases and lack of frequent follow-up by farmers and thus not used for the model verification. Crops grown in Tanzania were Chinese cabbage (*Brassica rapa* L.) and African nightshade (*Solanum* sp.).

APEX Model and Data Monitoring. APEX is a biophysical model that is capable of evaluating various field management practices (Williams et al. 1998) and is applied from the individual field/farms to small watershed scale (Clarke et al. 2017; Francesconi et al. 2014; Saleh and Gallego 2007; Tuppad et al. 2010; Wang et al. 2014; Worqlul et al. 2018a; Yin et al. 2009). APEX has flexibility in simulating crop growth of both annual and perennial crops (Williams et al. 2006), crop rotations, and various conservation practice (Gassman et al. 2010b; Yin et al. 2009). The no-till principle of CA was denoted in the model by providing zero tillage depth while cropping cycles were monitored and integrated into specific management input files. APEX model input data include land use/crops, soils, weather, field management practices, and, specifically for ArcAPEX user interface, a digital elevation model (DEM). A detailed description of the APEX model can be found in Williams et al. (2008a). Field management practices, such as conservation practice (no-till, mulching, and crop rotation), CT (tilled, no-mulch, and rotation), drip irrigation, fertilizers, and pesticides, were monitored separately for CA and CT plots. Farmers in the study sites grew various crops in different seasons (table 2).

Setup of the APEX model (version 1501) was made at all study sites separately for both management types (CA and CT) using the ArcAPEX user interface. User-defined polygons were created based on the size of the experimental plots—50 m^2 for each management—while the DEM was used to automatically derive the watershed characteristics. Moreover, soil, crops, and weather data were inputted to setup and run the model, and the field management practices were arranged in the APEX model management file format and provided to the model as input data. Crop growth is simulated based on the daily heat unit accumulation, which depends on daily average temperature and crop-specific base temperature (Williams et al. 2006). Crop growth occurs from planting to harvesting dates or when the accumulated heat units equal the potential heat unit (PHU; thermal heat units required by the plant to reach the physiological maturity) of the crops (Gassman et al. 2010b). No crop growth occurs when the temperature is below the crop base temperature. Crop growth here refers to annual/seasonal crops, not to perennial crops. The PHU was calculated for each crop based on long-term temperature, cropping period, and base temperature (Neitsch et al. 2011):

$$PHU = \sum_{d=1}^{m} HU, \qquad (1)$$

where

$$HU = \frac{(Tmax + Tmin)}{2} - TBSC;\ HU > 0,$$

where PHU is cumulative heat units required for a plant maturity, HU is the number of heat units accumulated on a day d ($d = 1$ on the day of planting), TBSC is crop-specific base temperature (°C), and m is the number of days required by the plant to reach maturity. The potential crop growth is constrained because of various environmental conditions. The major constraints estimated by APEX are stress conditions caused by lack of water, nutrients (N and phosphorus [P]), soil aeration, and temperature (low and high) (Wang et al. 2012; Williams et al. 2008a). The economic crop yield is estimated based on the harvest index and economic yield/aboveground biomass, and is expressed in equation 2 (Williams et al. 2008a):

$$YLD(i) = HIA(i) \times HE \times PSTF(i) \times STL(i), \qquad (2)$$

where $YLD(i)$ is the amount of crop removed from the field (t ha^{-1} of dry matter), $HIA(i)$ is the harvest index to estimate crop yield, $HE(i)$ is the harvest efficiency, $PSTF(i)$ is the pest factor, and $STL(i)$ is the aboveground biomass (t ha^{-1}). The harvest index is relatively stable and increases nonlinearly from zero to HI (potential harvest index) for stress-free conditions for a variety of environmental conditions (Williams et al. 2008a). A detailed description of each variable can be found in Williams et al. (2006).

Simulation of the Mulching Operation. To simulate the effect of the CA practice on soil quality and crop yield, mulch operations were set in the management file. The mulching operation was simulated as fertilization

Table 2
Crop rotations at the experimental sites.

		Growing periods											
Study sites	**Year**	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Dangishita	2015											Garlic	Garlic
	2016	Garlic	Garlic	Onion	Onion	Onion	Onion	Onion					
	2017			Garlic	Garlic	Garlic	Garlic	Garlic					
Robit	2015											Tomato	Tomato
	2016	Tomato	Tomato	Tomato	Garlic	Garlic	Garlic	Garlic	Garlic			Cabbage	Cabbage
	2017	Cabbage	Cabbage										
Yemu	2016								Sweet potato	Sweet potato	Sweet potato	Sweet potato	
	2017						Green pepper	Green pepper	Green pepper	Green pepper	Green pepper		
Mkindo	2016						Cabbage	Cabbage	Cabbage				
	2017						Nightshade	Nightshade	Nightshade				

with a custom fertilizer. The operation was set to spread the fertilizer on the soil surface and not incorporate it into the soil profile, while the custom fertilizer was created to replicate the average chemical composition of the phytomass used for the mulching. According to the value used by Izaurralde et al. (2006) to simulate the soil C dynamic with the Environmental Policy Integrated Climate (EPIC) model and supported by values reported in several other studies (Ghimire et al. 2017; Hughes et al. 1999; Johnson et al. 2007), the fraction of organic C of the phytomass used for mulching was set to 0.42. Based on the information retrieved from different publications, the organic N fraction was set to 0.0059 (Christensen 1985; Christensen 1986; Scheller and Joergensen 2008). For the simulation, the management file specifies the amount of phytomass applied (kg ha^{-1}). When the mulch is applied to the soil surface, the model estimates the fraction to be assigned to the structural and biomass litter and updates the C and N content of the organic pools used to simulate the dynamics of these two elements (Izaurralde et al. 2006). An important step is that the fraction of phytomass assigned to the litter is used to update the amount of residue that covers the soil surface. Finally, the residue affects the simulation of soil evaporation, surface runoff and percolation, and water and wind soil erosion. Moreover, the C and N introduced in the system will be slowly mineralized, the nutrients will be incorporated into the soil, and they will be available to sustain the plant growth.

Simulation of Carbon and Nitrogen. The simulation of soil organic matter dynamics in APEX follows the approach used in the Century model developed by Parton et al. (1987), Parton et al. (1993), and Parton et al. (1994) to simulate the coupled cycling of C and N in the soil (Izaurralde et al. 2006; Wang et al. 2008; Williams et al. 2008b). In this approach, C and N contained in the soil organic matter are divided into different pools (i.e., active [microbial], slow, and passive) characterized by different turnover times ranging from few days to years. Organic residues added to the soil surface are split into metabolic and structural litter compartments and are considered available for the mineralization processes. The potential transformations of different pools are calculated based on several factors such as substrate availability, temperature, and water content. The actual C and N transformations are calculated based on N supply available from each transformation. Detailed descriptions of C and N transformations and calculations can be found in Izaurralde et al. (2006) and Wang et al. (2008).

Model Calibration and Validation. Calibration and validation of the APEX model for simulating the hydrology of the system are the preceding phase in simulating crop growth. Assefa et al. (2018) validated the APEX model for hydrology at each study site, and the model parameters were used for this study. Then, the next step was to verify the APEX model for predicting crop yields at all study sites based on fresh vegetable weight measurements for various vegetables. APEX crop model calibration includes examining model outputs for stress conditions and modifying related parameters as well as some specific crop parameters. APEX crop model verification was carried out for each crop/vegetable type and cropping season separately for CA and CT practices. Measured vegetable yields—2015 to 2017 for Dangishita and Robit, 2016 to 2017 for Yemu and Mkindo sites—were divided into two data sets for calibration (three to five experimental plots) and validation (two to three experimental plots). Crop parameterizations were carried out within the acceptable limits (reasonable modification ranges) for the following parameters: biomass energy ratio (WA, also known as radiation use efficiency), optimal temperature for plant growth (TOP), maximum potential leaf area index (DMLA), and fraction of growing season when leaf area declines (DLAI) based on literature including Le (2017) and Wang et al. (2014). Le (2017) suggested the reasonable modification ranges for some crop parameters. Harvest efficiency can be slightly modified to account for factors that affect harvest success (Le 2017).

Model Performance Measures. The performance of the APEX model for predicting vegetable yields was evaluated at each study site and across the sites using the following statistical measures: Nash-Sutcliffe efficiency (NSE), percentage bias (PBIAS), root mean squared error (RMSE)–observation standard deviation ratio (RSR), and coefficient of determination (R^2) (equations 3 through 6):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Y_{oi} - Y_{si})^2}{\sum_{i=1}^{n}(Y_{oi} - \overline{Y}_m)^2}, \tag{3}$$

$$PBIAS = 100 \times \sum_{i=1}^{n}(Y_{oi} - Y_{si}) \Big/ \sum_{i=1}^{n} Y_{oi}, \tag{4}$$

$$RSR = \sqrt{\sum_{i=1}^{n}(Y_{oi} - Y_{si})^2} \Bigg/ \sqrt{\sum_{i=1}^{n}(Y_{oi} - \overline{Y}_m)^2}, \tag{5}$$

and

$$R^2 = \frac{[\sum_{i=1}^{n}(Y_{oi} - \overline{Y}_m)(Y_{si} - \overline{Y}_{ms})]^2}{\sum_{i=1}^{n}(Y_{oi} - \overline{Y}_m)^2 (Y_{si} - \overline{Y}_{ms})^2}, \tag{6}$$

where Y_{oi} and Y_{si} are the i^{th} observation and simulated value for the constituent being evaluated respectively; Y_m and Y_{ms} are the mean of observed data and simulated values respectively for the constituent being evaluated, and n is the total number of observations. NSE is a normalized statistic that compares the magnitude of residual variance and measured data variance (Moriasi et al. 2007). PBIAS refers to the average tendency of model simulation to be larger or smaller than observation. RSR is a standardized RMSE using observational standard deviation considering error-index and additional information. R^2 measures the degree of collinearity between simulated and measured data. A detailed description of statistical measures can be found in Moriasi et al. (2007). Once the model is properly calibrated and validated for hydrology and crops, the impacts of CA on soil quality (C and N) and crop yields were evaluated by comparing the model output for CA and CT.

Results and Discussion

The results and discussion are presented in two parts: (1) calibration and validation of APEX model for crop yield under CA and CT management practices, and (2) examination of the effects of CA on soil quality (C and N) and crop yield when compared to CT practices.

APEX Model Calibration and Validation: Crop Yield. As described before, the calibration of the APEX model for crop yield was conducted at each site (Dangishita, Robit, Yemu, and Mkindo) separately for CT and CA management practices. Crop parameters were modified (table 3) to improve model simulation for crop yields. The majority of crop parameters for garlic and onion were similar because the two vegetables belong to the same family. In contrast, cabbage parameters in Robit (Ethiopia) and Mkindo (Tanzania) are different because different varieties were cultivated at the two sites (cannonball in Robit and Chinese cabbage in Mkindo). Moreover, the pest damage cover threshold was adjusted (i.e., PARM [10] = 1) to allow the simulation of pest damage (particularly for CA plots) reported for the Mkindo. Tables 4 and 5 show observed and predicted vegetable yield for the calibration and validation periods, respectively.

Similarly, the APEX model was validated for its capability in simulating the yields for different sets of vegetables at different cli-

Table 3
Parameters' initial values (from the crop database in the model) and final (calibrated) values for conventional tillage practice.

	Crop parameters							
	WA		TOP (°C)		DMLA		DLAI	
Crops	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Garlic	30.00	30.00	29.00	32.00	1.50	1.30	0.60	0.60
Onion	30.00	28.00	29.00	30.00	1.50	1.30	0.60	0.60
Tomato	27.00	28.00	9.00	9.00	3.40	3.40	0.95	0.95
Garlic	30.00	30.00	29.00	32.00	1.50	1.30	0.60	0.60
Cabbage	19.00	21.00	24.00	22.00	3.00	3.75	1.00	1.00
Sweet potato	15.00	15.00	29.00	27.00	5.00	6.25	0.60	0.63
Green pepper	30.00	27.00	27.00	21.00	5.00	3.75	0.60	0.45
Cabbage	19.00	17.10	24.00	19.50	3.00	2.25	1.00	0.75
Nightshade	30.00	30.00	350.0	35.00	18.00	18.00	3.00	3.00

Notes: WA = radiation use efficiency. TOP = optimal temperature. DMLA = maximum potential leaf area index. DLAI = a fraction of growing season when leaf area declines.

Table 4
Mean observed and predicted fresh vegetable yields (calibration) for conservation agriculture (CA) and conventional tillage (CT) practices.

	Yield from CT (t ha^{-1})		Yield from CA (t ha^{-1})		
Crop	Observed	Predicted	Observed	Predicted	PBIAS (%) (CT | CA)
Garlic	2.80	3.70	4.00	3.70	−17.00 | 3.70
Onion	3.00	3.30	3.30	3.30	−11.00 | 0.00
Tomato	3.20	3.80	9.80	8.50	−21.00 | 14.00
Cannonball cabbage	18.30	18.40	21.10	18.60	−0.50 | 12.00
Sweet potato	10.10	11.90	15.70	12.00	23.70 | 24.80
Green pepper	3.40	3.70	3.60	3.70	−8.00 | −4.00
Chinese cabbage	3.80	4.00	2.00	2.40	−5.70 | −21.00
Nightshade	6.30	7.40	4.80	4.50	−16.80 | 9.10

Table 5
Mean observed and predicted fresh vegetable yields (validation) for conservation agriculture (CA) and conventional tillage (CT) practices.

	Yield from CT (t ha^{-1})		Yield from CA (t ha^{-1})		
Crop	Observed	Predicted	Observed	Predicted	PBIAS (%) (CT | CA)
Garlic	2.60	3.70	4.50	3.70	−21.00 | 8.40
Onion	2.70	3.30	3.00	3.30	−22.00 | −11.00
Garlic	3.10	3.80	4.10	4.00	−21.00 | 3.30
Tomato	4.00	3.80	9.50	8.50	4.00 | 0.00
Garlic	1.40	1.80	1.80	1.80	−23.00 | −12.00
Cabbage	19.60	18.40	20.40	18.60	6.10 | 8.90
Sweet potato	10.20	11.90	17.80	14.10	−3.80 | 20.00
Green pepper	3.00	3.70	3.40	3.70	−23.80 | −8.00
Chinese cabbage	3.90	4.00	2.00	2.40	−2.20 | −21.00
Nightshade	5.50	7.40	4.40	4.40	11.80 | 0.00
Chinese cabbage	3.00	3.70	4.00	3.70	−23.80 | 5.40

matic, soil, and environmental conditions for both CA and CT management (table 5). PBIAS was within ±25% for both calibration and validation at each study site.

Figure 2 shows the linear relationship between observed and predicted vegetable yields for calibration and validation of crop yield across the sites. Overprediction occurred often for CT, while underprediction occurred often for CA (table 4 and table 5) for the same crop. This could imply the improvement and decline of soil nutrients and crop yield more than it is captured in the model in CA and CT practice. Generally, APEX successfully simulated vegetable yields under CA and CT practices at all study sites.

The Impacts of Conservation Agriculture on Soil Carbon and Nitrogen Content. Soil organic C and N availability are repeatedly used as a soil quality indicator (Reeves 1997) and are essential elements of a sustainable agriculture system (Huang et al. 2016; Zhang et al. 2009). In particular, soil organic C is linked with many soil quality indicators and considered the most vital indicator of soil quality and productivity (Cannell and Hawes 1994; National Research Council 1993; Reeves 1997). Table 6 shows the comparison of N and C content under CA and CT systems across the four sites. The hypothesis was tested against 5% significance level and 10% significance level if the null hypothesis could not be rejected with 5%. A similar procedure is used (i.e., testing the hypothesis for 1%, 5%, and 10% significance level) by Edralin (2015) to evaluate short-term effects of CA on yield and irrigation water uses. When considering the sites in Ethiopia (Dangishita and Robit), the increment in soil C and N was significant at a 5% significance level. In general, the modeling results found that CA significantly ($p < 0.1$) improved total soil C and N across the sites when compared to CT practice during the study period (two years for Mkindo and Yemu, and three years for Dangishita and Robit). Soil C and N increased by about 6% and 4.1% across the sites under CA practice. The results were in agreement with previous studies in different parts of the world. Alvarez (2005) built an empirical model using paired data from 137 sites from published experiments in different parts of the world and estimated an increase in 12 t C ha^{-1} (after 25 to 30 years) under no-till practice as compared to CT system in the temperate region. Similarly, Huang et al. (2016) found 32% and 28% increments of soil organic C and total N, respectively, at the topsoil layer under the no-till system as compared to CT when using 10-year field experimental data in China.

Improvement of soil quality under CA can be attributed to several factors. Decomposition of organic mulch is mainly a biological process, where living organisms (microorganisms and soil macrofauna) decompose the organic mulch as a food source and release nutrients in the plant available form (mineralization). The successive decomposition of dead material and modified organic matter results in a stable

Figure 2

Observed and predicted crop yields for (a and c) conservation agriculture management and (b and d) conventional tillage. (a and b) Calibration and (c and d) validation are shown.

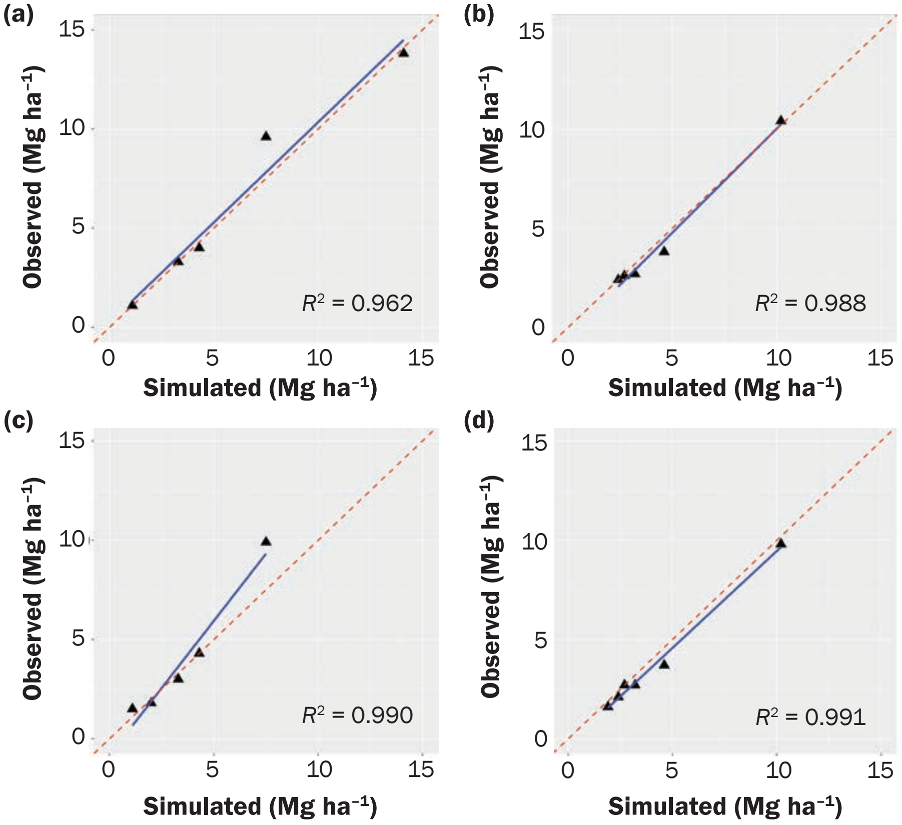


Table 6

Residual soil nitrogen and carbon at the end of the vegetable growing season for conservation agriculture (CA) and conventional tillage (CT) practices.

	Dangishita		Robit		Yemu		Mkindo	
Nutrients	CA	CT	CA	CT	CA	CT	CA	CT
Total nitrogen (kg ha^{-1})	5,571	5,337	5,881	5,663	26.70	26.30	108.40	107.40
Total carbon (kg ha^{-1})	56,380	53,423	54,496	51,067	278.00	277.70	1,062.00	1,057.00

Note: Total nitrogen and total carbon are the sums of their respective organic and inorganic components.

Table 7

Mean observed and predicted vegetable yields and nitrogen (N) stress across sites for conservation agriculture (CA) and conventional tillage (CT) practices.

Management	Observed yield (t ha^{-1})	Predicted yield (t ha^{-1})	N stress (d)
CA	7.90	7.20	1.70
CT	5.80	6.30	8.90
p-value	0.019**	0.08*	0.09*

**$p < 0.05$ *$p < 0.1$

compound, humus. As the humus material slowly decomposes, it results in the release of carbon dioxide (CO_2), energy, water, plant nutrients, and synthesized organic C compounds (Bot and Benites 2005). The decomposition of mulch material, along with no-till practice and diverse crop rotation, has positive impacts on improving soil quality. The reduction in N stress under CA (table 7) is an indicator of the improvement of soil quality as a result of soil nutrient enrichment from CA practice. A one-tailed paired *t*-test showed significantly lower N stress (1.7 days on average) in CA compared to CT (8.9 days on average) across the sites ($p < 0.05$) (table 7). This resulted in a significantly ($p < 0.05$) higher crop yield in CA plots when compared to CT as indicated by both the field experiment and model prediction across the study sites.

Soil C and N content (as well as crop yield, tables 4 and 5) were higher in Ethiopia sites (Dangishita and Robit) as compared to Yemu (Ghana) and Mkindo (Tanzania). This illustrates the degree of variability in the effects of CA practice on soil quality and crop yield, which can be attributed to various factors such as climatic conditions, water input, fertilizer input, landscape position, soil characteristics, the season and length of adopting CA practice, initial C and N content of the soil, and other site-specific conditions. In particular, the mulching in the two sites in Ethiopia was established around the end of the rainy season when the temperature starts to increase. This is also evidenced from the Qin et al. (2015) study, which found a higher positive effect of CA practice on crop yield from less water input, high N input, and at a high temperature. Farmers in Ethiopia applied less irrigation water to CA plots as compared to CT plots whereas the same amount of irrigation input was used for the other sites. It is difficult to speculate about the interaction between soil types and management strategies (i.e., CA and CT) because of different conditions present at each experimental site; however, despite the differences between soils, increases in soil organic C and N were simulated at all sites. It is worth noting that, in all the cases, the model simulated increased soil organic C and N content only in the top 20 to 30 cm of the soil.

Summary and Conclusions

Field experiments were conducted on a total of 43 paired plots (CA and CT practices) at four study sites in SSA: Dangishita and Robit (Ethiopia), Yemu (Ghana), and Mkindo (Tanzania). Biophysical data were monitored for both management practices. Crop yield data of a variety of vegetables were used to calibrate and validate the APEX model. The well-calibrated model was then used to quantify the effects of CA with drip irrigation on soil quality and crop yield improvements as compared to CT practice. The APEX model successfully simulated crop yield at each study sites (PBIAS ≤ ±25) and across the sites (NES > 0.90, PBIAS ≤ ±15, RSR < 0.1, $R^2 > 0.95$) for both calibration and validation data sets.

Soil C and N were used as indicators of soil quality in CA and CT practices. The final total C and N were increased at each study site under CA practice. A significant final total C increase was observed under CA at Dangishita (5.5%) and Robit (6.7%) sites. Similarly, the final total N was significantly increased under CA at Dangishita (4.4%) and Robit (3.8%) sites. The increase in final total C and N under CA was relatively lower at Mkindo and Yemu sites. Generally, soil C and N were increased under CA by about 6% and 4.1% across the sites when compared with CT. Therefore, crop yield was significantly improved under CA with about 37.4% increases across the sites when compared to CT. The rate of soil quality and crop yield improvement in Dangishita and Robit (Ethiopia) were higher when compared with other sites. Conservation agriculture with drip irrigation was a feasible local strategy for small-scale agriculture to improve crop production and sustain livelihood in the region while enhancing the ecosystem.

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