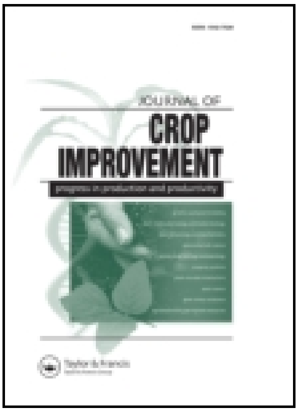

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Application of DSSAT Crop Models to Generate Alternative Production Activities Under Combined Use of Organic-Inorganic Nutrients in Rwanda

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Application of DSSAT Crop Models to Generate Alternative Production Activities Under Combined Use of Organic-Inorganic Nutrients in Rwanda

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The low agricultural productivity of Rwanda reflects the poor soil fertility status caused by a low organic matter and high soil acidity that characterizes a large part of the country. Experimental trials have shown that a combined use of organic and inorganic fertilizers can increase crop yield. However, there are no guidelines for combined nutrients of different sources and qualities. Crop growth models can assist in the evaluation of the integration of organic and inorganic fertilizers. The Decision Support System for Agrotechnology Transfer (DSSAT) presents a collection of such crop models. The objective of this study was to determine alternative production activities through yield prediction of several crops under combined use of organic and inorganic fertilizers on Oxisols and Inceptisols in eastern Rwanda and to determine the best fertility management options. The DSSAT crop models were used to quantify the alternative production activities. The simulation of crop yield showed that predicted crop yield was distinctly higher than the actual yield for the current small-scale farming practices common in the region. The predicted yields for beans (Phaseolus vulgaris)*, groundnut* (Arachis hypogaea)*, and cassava*

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(Manihot esculenta) *were approximately the same for all treatments, whereas the combined application of Tithonia diversifolia and Diammonium phosphate appeared to predict higher yields for maize* (Zea mays) *and sorghum* (Sorghum bicolor). *Yield prediction for all crops was higher on the Inceptisols than on the Oxisols because of the better chemical and physical conditions of Inceptisols. This is in line with reality.*

KEYWORDS *Rwanda, DSSAT, crop simulation models, organic fertilizer, inorganic fertilizer, crop yield*

INTRODUCTION

Rwanda has the highest population density in Africa, and population growth is putting an ever-increasing pressure on farmland. This pressure on land and water resources leads to the degradation of these resources, which often results in a loss of the production capacity and increasing food insecurity. Rwandan agriculture is currently unable to meet the food needs of the population. In fact, national agricultural production covers only 87% and 70% of the national needs based on the minimum recommended calorie and protein requirements, respectively (Ministry of Agriculture and Animal Resources [MINAGRI] 2004).

Low agricultural production follows from the low soil-fertility status, low organic matter content, and high soil acidity characterizing a large part of Rwanda soils, except for the marshy and volcanic land (Groupe D'Expertise, de Conseil et d'Appui au Développement [GECAD] 2004). Traditional techniques of soil fertility regeneration, such as fallow, are no longer possible because of the exiguity of land. Use of agricultural inputs such as inorganic fertilizers remains insignificant in spite of of declining soil fertility (MINAGRI 2005) because the prices of inorganic fertilizer are beyond the financial means of small-scale farmers. Furthermore, used alone, mineral fertilizers can lead to problems, such as reduced soil fertility, soil acidification, and groundwater pollution, unless corrective measures are taken (Kwaye, Dennis, & Asmah 1995; Bekunda, Bationo, & Ssali 1997). Organic fertilizers, such as farmyard manure, crop residues, and compost, are well accepted and have shown promising results in Rwanda (Dreschsel, Steiner, & Hagerdon 1996; Balasubramanian and Sekayange 1992). However, its production and availability can be limited by labor and land shortage for raising livestock. Other organic systems, such as green manuring with leaf biomass from shrubs and trees (e.g., *Calliandra*, *Tithonia*, *Tephrosia*), have been shown to be useful for improving soil fertility (Kwesiga & Coe 1994), although use of such practices by farmers is limited because of land shortage to grow those shrubs and trees. The use of organic and inorganic fertilizers relies on different household resources, with inorganic fertilizers requiring financial capital and organic fertilizers mainly requiring labor and land (Place et al. 2003).

Numerous field trials have repeatedly shown the beneficial effects of the combined use of organic and inorganic nutrients on sustainability. This combinatorial approach has been proven to increase crop yield while maintaining soil organic matter and reducing soil erosion (Palm, Myers, & Nandwa 1997). Additionally, increased nutrient availability and residual effects are associated more with combined organic and inorganic fertilizer use than with inorganic fertilizers applied alone (Houngnandan 2000). Given the high cost and uncertain accessibility of inorganic fertilizers in many developing countries, the goal of the combined use of organic and inorganic fertilizers should be to provide as much nutrients as possible through organic materials, making up the shortfall of the limiting nutrients through inorganic fertilizers.

Crop growth simulation models offer possibilities to improve agricultural productivity by generating alternative pruduction activities focused on sustainability (Rabbinge 1995; Tsuji et al. 1998; Alagarswamy et al. 2000). Such models have been used to generate alternative production activities given the natural environment and under the crop and soil-fertility management specified.

In yield trials conducted in Rwanda, the combined use of organic and inorganic fertilizers showed a positive effect on crop yield (Dreichsel et al. 1998; Rutunga et al. 1998; Ngaboyisonga et al. 2007). Yet there is a lack of rational guidelines on their management (dosage and type of fertilizer). Crop simulation models can assist in evaluating the proportions at which nutrients of different sources and qualities are combined to predict crop yield. The Decision Support System for Agrotechnology Transfer (DSSAT) is a collection of such crop simulation models that integrate the effects of daily weather data with soil characteristics, crop phenotype, and management practices (Jones et al. 2003; Hoogenboom et al. 2004). The program allows users to generate alternative production practices through the prediction of crop yield and evaluate different options to maximize profit and/or to minimize losses of nutrients. In a recent study, Soler et al. (2011) evaluated the performance of DSSAT for simulating soil organic carbon dynamics in Burkina Faso. However, DSSAT has not yet been used for exploring the suitable combined use of organic and inorganic fertilizers under the conditions of the tropical sub-Saharan Africa region.

The objective of this paper was to determine alternative production activities of several crops under combined use of organic and inorganic fertilizers on Oxisols and Inceptisols in eastern Rwanda and to determine the combined use of organic and inorganic fertilizers, which predict high yield for each crop. The DSSAT crop simulation models were used to quantify alternative production activities through the estimation of crop yield.

MATERIALS AND METHODS

Description of Study Area

The Umutara province, with an altitude between 1,000 m and 1,500 m, belongs entirely to the agro-climatic zone of the Central Bugesera and the Savannahs of the East, which is the driest agro-climatic region of Rwanda. The climate of the province is characterized by four seasons where rainy and dry seasons alternate annually. The seasons are defined on the basis of their precipitation regime (Gontanegre, Prioul, & Sirven 1974). Figure 1 illustrates the average annual pattern of rainfall and potential evapotranspiration of Umutara. The climate thus allows two cropping seasons annually; season A corresponding to the short rainy season from September to January, and season B corresponding to the long rainy season from February to June (Verdoodt & Van Ranst 2003). Despite the fact that Umutara province is positioned within one agro-climatic zone, there could be high spatial and temporal variability in rainfall that has a serious impact on crop production (Verdoodt & Van Ranst 2006; Ghent University 2003). The temperature in the province shows little variation throughout the year, and the average annual temperature can exceed 21°C (Ghent University 2003).

The pedology of Umutara is quite diverse, notwithstanding that it is a small region. The main soil types of the region are defined as Inceptisols and Oxisols based on the United States Department of Agriculture soil taxonomy (USDA 1999), and together they occupy 60% of total land area. Oxisols are very highly weathered soils characterized by low content of cation exchange capacity (CEC) and high clay content. Although most Oxisols have an extremely low soil fertility, they can be productive if lime and fertilizer

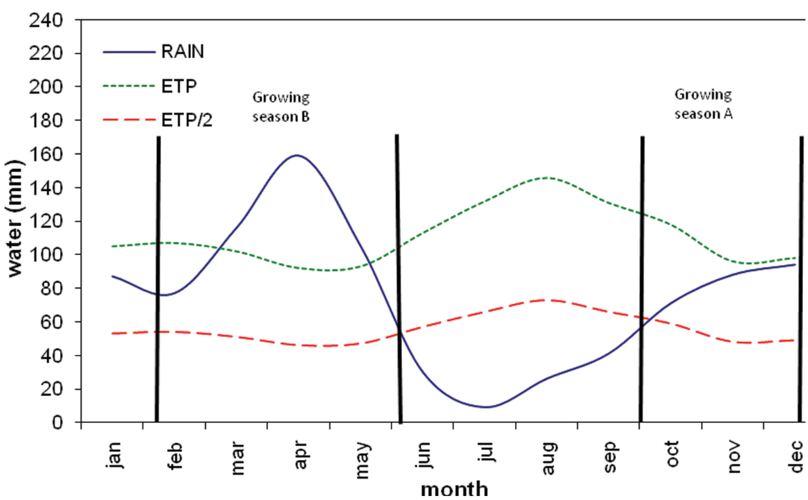

FIGURE 1 Annual variability in rainfall and potential evapotranspiration for Umutara (Bidogeza 2003) (color figure available online).

are applied. Inceptisols in the humid tropic are poor in nutrients but still richer than Oxisols and they have a greater CEC (FAO 2001).

The family exploitations cover an area of 63,711 ha, including cultivated land, land put in fallow, pastures, wooded areas, and land reserved for other uses (e.g., roads and buildings). Cultivated land accounts for 68% of the cultivable land, whereas the fallow, woodland, and other uses account for 26%, 2%, and 4%, respectively (MINAGRI 2002). With respect to the importance of the different crops cultivated in the province of Umutara, the highest percentage of the cultivated land is occupied by cereals (33%), followed by tuber crops (29.5%), leguminous crops (21%), and bananas (15%) (MINAGRI 2002). Umutara's cattle currently constitute a large share of livestock in Rwanda. Cattle have traditionally represented an important source of income and manure for smallholder farms.

Brief Description of DSSAT

The Decision Support System for Agrotechnology Transfer (DSSAT) is a microcomputer software designed to facilitate the evaluation and application of the crop models for different purposes (Jones et al. 2003; Hoogenboom et al. 2004). DSSAT was developed by the International Benchmark Sites Network for Agrotechnology Transfert (IBSNAT 1993) and has been used for more than 25 years by researchers worldwide. DSSAT is a collection of independent programs that operate together; crop simulation models are the core part of the software package. Figure 2 summarizes the framework of the DSSAT, which comprises the following main components: 1) database management system to input, organize, store, retrieve, analyze, and display data on crops, soils, and weather; 2) a set of crop models to simulate crop growth, development, and yield; and 3) application programs to analyze, display, and evaluate the model outcomes with the observed data.

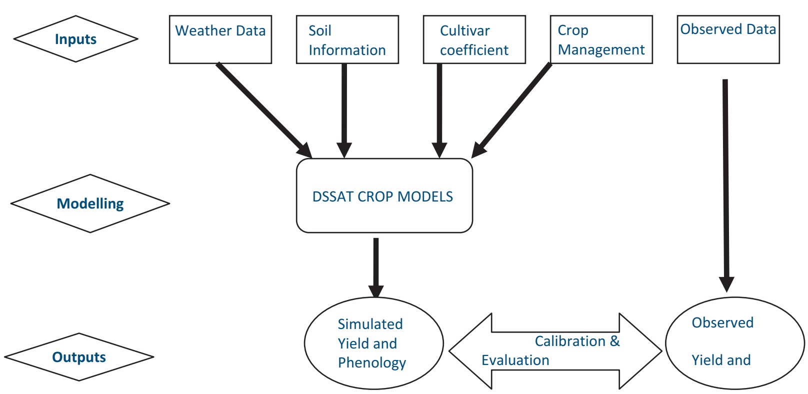

FIGURE 2 Schematic relationships between the three components of DSSAT (color figure available online).

The DSSAT crop models simulate growth, development, and yield of crops grown on a uniform area of land under a set of management conditions. As part of the simulation, the models consider changes in soil water, carbon, and nitrogen that take place under the cropping system across time (Jones et al. 2003). By simulating probable outcomes of crop-management strategies, DSSAT offers users information to rapidly appraise new crops, products, and practices for adoption. The recent release of DSSAT version 4.5 incorporates 27 different crops that include various crops relevant for Rwanda. The new version facilitates the creation and management of experimental, soil, and weather data file (Hoogenboom et al. 2010).

Data Requirements

Minimum Data Set (MDS) For Model Operation

The MDS refers to a minimum set of data required to run DSSAT. The contents of such a dataset have been defined by experts from IBSNAT and the Independent Communications Authority of South Africa (ICASA; Hunt, White, & Hoogenboom 2001; Jones et al. 2003), and are shown in Table 1. They include data on the site where the model is to be operated, daily weather, local soil surface and profile characteristics, and crop management.

Site and Weather Data

The study area is located in the northeast at 30°20´ of eastern longitude and 1°20′ southern latitude with an average elevation of 1,490 m

TABLE 1 Minimum data set needed to run the simulation models of DSSAT

Type	Content
Site	Latitude and longitude, elevation; Average annual temperature; slope and aspect; drainage (type, spacingand depth); surface stones (coverage and size)
Weather	Daily values of incoming solar radiation; Daily maximum and minimum air temperature; Rainfall.
Soil	Classification using local system and (to family level) the USAD-NRCS taxonomy system. Basic profile characteristic by soil layer: saturated drained upper limit, lower limit; bulk density, organic carbon; pH; root growth factor; and drainage coefficient.
Crop management	Cultivar; planting date, depth and method; planting density; row spacing and direction; Irrigation and water management, dates, methods and amounts or depths; Fertilizer (inorganic); Residue (organic fertilizer) applications (material, depth of incorporation, amount, and nutrients concentrations); tillage; and Harvest schedule.

Source: adapted from Jones et al. (2003).

(Bidogeza 2003). The soil data were obtained from the database of the Rwandese-Belgian Soil Map project (Ghent University 2002) and the Rwanda Agriculture Research Institute (unpublished data from L. Nabahungu). In Umutara, the weather data were recorded by the two meteorological stations located at Gabiro (1°19′1″S and 30°19′58″E) and Nyagatare (1°17′26″S and 30°19′58″E) at an elevation of 1,412 m and 1,450 m, respectively. Daily precipitation and maximum and minimum temperatures at the Gabiro meteorological station were recorded in 1970. The daily insolation records for Kigali were only available in 1970, and consequently data from the same year had to be used in Gabiro. For the Nyagatare meteorological station, complete daily data on precipitation, maximum and minimum temperatures, and solar radiation were available for 2006. Agricultural years of 1970 and 2006 were considered for simulation because complete daily weather data were available for these years, as required for the crop models. The monthly weather data for 1970 for Gabiro and for 2006 for Nyagatare are summarized in Table 2. The year 1970 was a relatively wet year, whereas 2006 was more or less average.

Soil Data

The soil data were obtained from the soil profile database of the Rwandese-Belgian Soil Map project (Ghent University 2002). Soil profiles for the two dominant soil series, Akagera and Rwakibare, representing Oxisols and

TABLE 2 Monthly average value of weather variables used for the crop model simulation

	Solar Radiation (MJ/m^2)		Maximum Temperature (°C)		Minimum Temperature (°C)		Total Rain (mm)		Average rainfall from 1931–1982 (mm)
Months	1970	2006	1970	2006	1970	2006	1970	2006	
Monthly values									
Jan	17.3	15.6	25.9	28.5	15.0	14.3	97.80	49.00	87.0
Feb	17.1	16.1	27.1	29.0	14.8	15.4	90.90	107.0	77.0
Mar	19.0	16.1	27.6	26.9	15.2	15.7	159.7	110.4	116
Apr	16.3	17.0	24.5	25.9	15.4	16.0	205.8	195.2	159
May	17.2	17.3	24.9	27.0	15.3	16.0	94.10	34.00	105
Jun	20.5	14.4	25.9	28.5	14.7	13.8	18.50	0.200	30.0
Jul	16.2	14.0	25.2	28.9	15.5	15.0	7.300	13.40	9.00
Aug	19.8	17.7	27.1	28.8	15.3	15.6	20.00	34.80	26.0
Sept	19.8	18.2	26.1	28.8	14.8	15.9	44.70	37.00	41.0
Oct	16.5	18.0	26.6	28.0	15.1	16.4	29.40	83.60	71.0
Nov	16.8	14.8	25.1	24.7	15.0	16.1	178.7	162.4	88.0
Dec	17.8	14.3	25.1	25.3	14.7	16.2	79.30	84.40	94.0
							1126.2*	911.4*	903*

*Total annual rainfall.
Source: Ghent University (2002) and Nabahungu (2010)

TABLE 3A Chemical and physical properties of soil series Akagera (Inceptisols)

Soil depth (cm)	Master horizon	Organic carbon (%)	Total nitrogen (%)	Clay (%)	Silt (%)	pH in water	CEC Cmol Kg^{-1}	Bulk density (g cm^{-3})	Saturated yydraulic conductivity (cm h^{-1})
0–16	A1	1.23	0.11	22.7	16.4	5.7	7.4	1.18	0.43
17–30	A2	0.91	0.08	30.1	17.2	5.6	7.5	1.15	0.43
31–43	BA	0.68	0.07	34.1	17.9	5.7	7.8	1.33	0.43
44–66	B1	0.52	0.05	35.7	17.8	5.5	7.2	1.41	0.12
67–80	B2	0.48	0.05	38.9	19.6	5.4	7.1	1.25	0.23
81–100	B3	0.39	0.04	39.4	19	5.3	7.2	1.19	0.23
101–130	C1	0.36	0.04	40.1	19.8	5.4	6	1.17	0.06
131–160	C2	0.35	0.04	39.1	20.4	5.8	7.2	1.49	0.23

Source: Ghent University (2002).

TABLE 3B Chemical and physical properties of soil series Rwakibare (Oxisols)

Soil depth (cm)	Master horizon	Organic carbon (%)	Total nitrogen (%)	Clay (%)	Silt (%)	pH in water	CEC Cmol Kg^{-1}	Bulk density (g cm^{-3})	Saturated hydraulic conductivity (cm h^{-1})
0–25	A	0.84	0.07	21.9	8.5	6	6.2	1.51	0.43
26–48	AB	0.41	0.05	33.8	6.5	6.3	5.8	1.56	0.43
49–74	Bo1	0.27	0.04	38	6.7	5.1	5.3	1.57	0.12
75–115	Bo2	0.16	0.02	38.5	8.4	4.6	5.7	1.59	0.12

Source: Ghent University (2002).

Inceptisols (USDA soil taxonomy), respectively, were selected for simulation. Oxisols and Inceptisols account for 40% and 20% of all soils in the Umutara region, respectively. The physical and chemical characteristics of these soil series are listed in Table 3a and Table 3b, respectively.

Crop Management

The crops used in simulating the growth and yield included maize, sorghum, dry bean, groundnut, and cassava. These crops are among the most important crops in the region because of their role in the diet of local people. Other crops of importance, such as banana and sweet potatoes, were not considered in the simulation because they are currently not part of DSSAT. For each crop, one cultivar was evaluated. The choice of the cultivar depended on its growth cycle. Cultivars from tropical environments with short growth cycles were favored.

Crop management referred to the field operations performed during the growing season. Management practices, such as sowing date, harvest date, rotation, plant density, row spacing, and planting depth, were based on the recommendations from the Ministry of Agriculture to intensify farming (MINAGRI 2008).

Soil Fertility Management

The soil-fertility management simulated was based on a combination of organic materials and inorganic fertilizer. Table 4 contains descriptions of three organic soil fertility practices considered for each crop and alternatively simulated in this study. Crop residues and farmyard manure have been chosen because of their accessibility to and affordability by small-scale farmers. *Tithonia diversifolia* is a green-manure shrub known to supply high nutrient concentrations and is relatively widespread in Rwanda (Mukuralinda 2007). The nutrient concentrations of organic materials used in the simulation are shown in Table 5.

The inorganic fertilizer simulated was diammonium phosphate (DAP), one of the chemical fertilizers recommended by the Ministry of Agriculture in Rwanda to intensify agriculture. The ministry has recommended the use of manure and DAP at the rates of 10 t ha^{-1} and 125 kg ha^{-1}, respectively (MINAGRI 2008). However, these proportions are beyond the financial means of small-scale farmers and remain exaggerated in view of the current average use of inorganic fertilizer in Rwanda, which is 10 kg ha^{-1} (Kalibata

TABLE 4 Nutrient concentration of organic materials used in the simulation

Nutrients (%)	Crop residues	Farm yard manure	Green manure *Tithonia diversifolia*
N	0,66	1,51	3.3
P	0,07	0,14	0.4
K	0,3	0,91	4.1

Source: Drechsel and Reck (1998) and Mukuralinda (2007).

TABLE 5 Beans yield (t ha^{-1}) under different combination of organic materials and chemical fertilizer

Season	Season A						Season B					
Soil Series	Akagera (Inceptisols)			Rwakibare (Oxisols)			Akagera (Inceptisols)			Rwakibare (Oxisols)		
Year Treatments	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean
T1	1.6	2.0	1.8	1.1	1.6	1.4	1.7	1.9	1.8	1.6	1.6	1.6
T2	1.6	2.1	1.8	1.1	1.5	1.3	1.7	2.0	1.8	1.6	1.5	1.6
T3	1.6	2.0	1.8	1.2	1.6	1.4	1.6	2.0	1.8	1.6	1.7	1.7

T1: Crop residues (2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); T2: Farmyard manure 2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); and T3: *Tithonia diversifolia* (2,500 kg ha^{-1}) + Diammonium phosphate (30 kg ha^{-1}).

2010). Therefore, 25% of the recommended inputs have been applied in the simulation model. This may be within reach of the small-scale farmers with limited land and financial means. The treatments in the simulation included: i) T1, crop residues (2,500 kg ha^{-1}) and DAP (30 kg ha^{-1}); T2, farmyard manure (2,500 kg ha^{-1}) and DAP (30 kg ha^{-1}); and T3, *Tithonia diversifolia* (2,500 Kg ha^{-1}) and DAP (30 kg ha^{-1}).

RESULTS AND DISCUSSION

Model Calibration and Evaluation

It is very important to establish the credibility of DSSAT crop model outputs with the real data and determine its suitability for the intended purpose. However, the absence of experimental plot data hampered an appropriate calibration and a full evaluation of the performance of the DSSAT crop models. Crop growth simulation models have been applied in Rwanda previously by Verdoodt and Van Ranst (2006), including evaluation with yields reported by small-scale farmer interviews. Hence, the evaluation of DSSAT crop models was based on a comparison of simulated yield without soil fertility practices, with average yield observed under the current small-scale farming in the region. DSSAT crop models were calibrating using crop-management practices such as planting date, planting method, planting density, planting depth, and row spacing. These crop management practices were based on the recommandations from the Minstry of Agriculture to intensify farming (MINAGRI 2010). The yield of several crops simulated without soil fertility-management practices and yield under small-scale farming in the region are shown in Figure 3. Bean, groundnut, and sorghum yield under

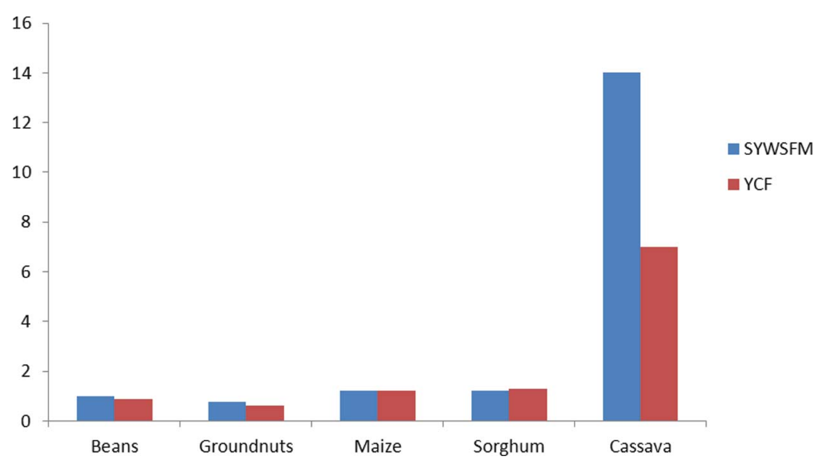

FIGURE 3 Simulated crop yields in t ha^{-1} without soil fertility management (SYWSFM) and crop yields under small-scale farming (YCF) (color figure available online).

current small-scale farming were noted to be slighly different from the simulated yield, whereas maize yields were equal for the two options. Simulated cassava yields were considerably higher than yield under the current small-scale farming. However, cassava cultivars can have potential to yield three or four times more than the native cultivars (Okeke 1988). Although the evaluation was limited because of the lack of detailed experimental data, it gave an indication of the perfomance of the DSSAT crop models. Thus, comparison of the simulated yields without soil-fertility practices and yields under current small-scale farming revealed satisfactory crop model performance with respect to common beans, groundnut, maize, and sorghum, while predicted cassava yields were overestimated.

Comparison of Soil-Fertility Management

The prediction of bean yield under different combinations of organic materials and inorganic fertilizer was noted to be different from the actual bean yield that has been recorded in the region under current small-scale farming practices, which is 0.8 t ha^{-1} on average (Table 5; Bidogeza et al. 2012). These results show a slight increase in predicted yield in response to the nitrogen level of organic fertilizer. For each year simulated, yields from all the treatments were approximately the same while their nitrogen concentrations differ. Because common beans can fix nitrogen, the nitrogen requirements are satisfied for the most part by the symbiotic fixation. Consequently, nitrogen from the combined organic materials and chemical fertilizer may not bring much added value for increasing crop yield. The simulated bean yield indicated a higher yield in 2006 than in 1970 for all management scenarios. Although 1970 showed a higher amount of rainfall than 2006, a well-distributed rainfall during the development phase of beans was observed in 2006. Good bean yield depends on moderate but well-distributed rainfall, i.e., 80 to 120 mm during vegetative growth (Raemaeckers 2001). The rainfall recorded during the vegetative growth in 2006 was 85 mm and 114 mm in seasons A and B, respectively; while 1970 recorded 31 mm and 131 mm in seasons A and B, respectively.

Similarly to bean, simulated groundnut yield under different combinations of organic materials and inorganic fertilizer was noted to be different from the yield under current small-scale farming in the region, which is 0.6 t ha^{-1} on average (Bidogeza et al. 2010). Table 6 summarizes the predicted yield of groundnut under a combined use of organic and inorganic fertilizer. All management scenarios showed approximatly the same yield. It has been shown that the rainfall regimes in Rwanda allow for optimal groundnut growth. However, hot and sunny conditions can make a difference in yield because groundnut is a drought-tolerant crop (Ghent University 2003). It is known that the rate of transpiration is favored with hot and sunny conditions among others (Beckett 1986). Although 1970 and 2006 had sufficient

TABLE 6 Groundnuts yields (t ha^{-1}) under different combination of organic materials and chemical fertilizer

Season	Season A						Season B					
Soil Series	Akagera (Inceptisols)			Rwakibare (Oxisols)			Akagera (Inceptisols)			Rwakibare (Oxisols)		
Year Treatment	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean
T1	2.0	2.3	2.2	1.6	2.1	1.8	1.7	1.5	1.6	1.5	1.2	1.3
T2	2.0	2.3	2.1	1.5	2.0	1.8	1.7	1.5	1.6	1.5	1.2	1.3
T3	1.9	2.3	2.1	1.5	2.0	1.7	1.7	1.5	1.6	1.5	1.2	1.4

T1: Crop residues (2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); T2: Farmyard manure 2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); and T3: *Tithonia diversifolia* (2,500 kg ha^{-1}) + Diammonium phosphate (30 kg ha^{-1}).

rainfall to meet the requirements of groundnut during the growing season, season A of 2006 produced a higher yield than season A of 1970, whereas season B of 1970 produced a higher yield than season B of 2006. This is possibly due to the higher transpiration of groundnut simulated for season A of 2006 (176 mm) than in season A of 1970 (150 mm). Similarly, in season B of 1970, 150 mm of transpiration was simulated compared with 126 mm for season B of 2006.

The combination of organic materials and chemical fertilizers showed a consistently higher maize yield (Table 7) than the average actual yield under current small-scale farming in the region, which is 1.21 t ha^{-1} (Bidogeza et al. 2010). These results indicated that yield in the model positively responded to an increase in N rate. The smallest increase in maize yield that was predicted was for the combined crop residue and chemical fertilizer application, whereas the combined use of green manure and chemical fertilizer showed

TABLE 7 Maize yields (t ha^{-1}) under different combination of organic materials and chemical fertilizer

Season	Season A						Season B					
Soil Series	Akagera (Inceptisols)			Rwakibare (Oxisols)			Akagera (Inceptisols)			Rwakibare (Oxisols)		
Year Treatment	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean
T1	3.8	3.7	3.8	2.3	3.6	3.0	3.8	3.5	3.6	3.2	2.4	2.8
T2	5.2	4.8	5.0	3.3	4.8	4.3	5.1	3.7	4.4	4.1	2.9	3.5
T3	6.1	5.4	5.7	5.6	5.4	5.5	5.8	3.2	4.5	4.6	3.0	3.8

T1: Crop residues (2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); T2: Farmyard manure 2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); and T3: *Tithonia diversifolia* (2,500 kg ha^{-1}) + Diammonium phosphate (30 kg ha^{-1}).

a significant increase. The smaller increase for the combined crop residue and chemical fertilizer treatment was because of the lower nitrogen content of crop residues. Similar to bean yield, the simulated maize yield was higher for the Akagera soil series than for the Rwakibare soil series because of the better chemical and physical conditions of the Akagera soils.

Simulated sorghum yield was higher under various combinations of organic materials and chemical fertilizer than the yields recorded under current small-scale farming in the region, which is 1.3 t ha^{-1} on average (Table 8; Bidogeza et al. 2010). These results showed that sorghum responded positively to an increase in the N application rate. The smallest simulated increase in sorghum yield was observed for the combined crop residue and chemical fertilizer application, whereas the highest increase was found for the combined green manure and chemical fertilizer. Simulated sorghum yield for season A for both 1970 and 2006 was quite a bit higher than the yield for season B. This was most likely because of the drought observed during the grain-filling phase in season B of 1970 and 2006. Only 2 mm of rainfall were recorded in season B of 2006, whereas a record 7 mm was observed in season B of 1970 during the grain-filling phase. In season A, an average record of 162 mm of rainfall was noted for both 1970 and 2006 during the grain-filling period. This is consistent with the results of Benech-Arnold, Fenner, and Edwards (1991), who also found a lower rate of dry-matter accumulation for sorghum when the grain-filling phase was confronted with drought.

The predicted cassava yields did not respond to an increase in nitrogen content of organic materials (Table 9). Hence, all the management scenarios showed approximately the same yields. The results of the model indicated that predicted cassava yields in 2006 were higher than in 1970, possibly because of the sufficiently well-distributed rainfall in the first six months of the 2006 growth season. In addition, year 1970 was too wet with rainfall

TABLE 8 Sorghum yields (t ha^{-1}) under different combination of organic materials and chemical fertilizer

Season	Season A						Season B					
Soil Series	Akagera (Inceptisols)			Rwakibare (Oxisols)			Akagera (Inceptisols)			Rwakibare (Oxisols)		
Year Treatment	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean	1970	2006	Mean
T1	3.9	4.0	3.9	3.5	3.3	3.4	3.3	3.4	3.3	2.5	2.8	2.7
T2	5.8	5.6	5.7	5.2	5.3	5.3	3.7	3.8	3.7	3.8	3.1	3.4
T3	6.1	6.0	6.0	5.2	5.7	5.3	3.1	3.7	3.4	5.3	3.1	4.2

T1: Crop residues (2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); T2: Farmyard manure 2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); and T3: *Tithonia diversifolia* (2,500 kg ha^{-1}) + Diammonium phosphate (30 kg ha^{-1}).

TABLE 9 Cassava yields (t ha^{-1}) under different combination of organic materials and chemical fertilizer

Season	Season A			Season B		
Soil Series	Akagera (Inceptisols)			Rwakibare (Oxisols)		
Year Treatment	1970	2006	Mean	1970	2006	Mean
T1	16.6	20.1	18.4	15.0	17.6	16.3
T2	16.5	18.9	17.8	15.0	17.6	16.3
T3	16.5	19.0	17.7	14.9	17.6	16.2

T1: Crop residues (2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); T2: Farmyard manure 2,500 kg ha^{-1}) + Diammonium phosphate (30kg ha^{-1}); and T3: *Tithonia diversifolia* (2,500 kg ha^{-1}) + Diammonium phosphate (30 kg ha^{-1}).

unevenly distributed across the first six months of 1970, which is not favorable for cassava growth.

The crop-model results were also compared with yield data from national and tropical regions that have reliable information for good commercial rainfed and irrigated yield levels (Sys et al. 1993), rainfed yield attained under common farming practices (Sys et al. 1993), and yields attained under controlled soil-fertility management (MINAGRI 2008). A comparison of the simulated and reported crop yield is shown in Table 10.

The simulated bean yield corresponded well with good commercial yield levels attained under irrigated conditions and yields generally reported in Rwanda under controlled fertilizer management. However, the simulated bean yield for the combined organic and inorganic fertilizers was higher than the average farmer's rainfed yield. Simulated groundnut yield under combined organic and inorganic fertilizers was approximately the same as good commercial rainfed yield, whereas good commercial irrigated yield was higher the simulated groundnut yield.

Simulated maize yield was to some extent in the range of the reported yield from good commercial practices under rainfed and irrigation

TABLE 10 Comparison of the predicted and reported crop yields (t ha^{-1})

Crop	SYOI[a]	GCRY[b]	GCIY[c]	AFRY[d]	YCC[e]
Common beans	1.40–1.90	1.0–1.5	1.5–2.5	0.5–1.0	1.5–2.8
Groundnut	1.40–2.20	2.0–3.0	3.5–4.5	1.0–2.0	1.0–3.0
Maize	2.80–5.80	6.0–9.0	6.0–9.0	–	2.0–5.0
Sorghum	2.70–6.00	2.5–3.5	3.5–5.0	1.3–2.0	2.0–4.0
Cassava	15.0–18.0	30–40	35–50	5.0–15	20–50

(SYOI) simulated yield under organic and inorganic fertilizers (from DSSAT); (GCRY) good commercial rainfed yield (Sys et al. 1993); (GCIY) good commercial irrigated yield (Sys et al. 1993); (AFRY) average farmer rainfed yield (Sys et al. 1993); and (YCC) yield under controlled conditions (MINAGRI 2008).

conditions. Furthermore, simulated maize yield was also within close range of the yield reported under controlled management conditions of Rwanda. In addition, simulated maize yield agreed with maize yield for combined organic and inorganic material trials conducted in southern Rwanda, which ranged from 2.6 t ha^{-1} to 7.4 t ha^{-1} (Mukuralinda 2007; Ruganzu 2009).

Simulated sorghum yield was very similar to the good commercial yield that can be obtained under irrigated conditions and under controlled management as generally reported in Rwanda. However, simulated sorghum yield was overestimated for good commercial rainfed yield and for rainfed yields under common farmers' management practices.

With respect to the yields attained under the different options (Table 11), predicted cassava yields were clearly underestimated by DSSAT compared with reported yields of good commercial rainfed, good commercial irrigated yields, and yields under controlled soil-fertility management. Nevertheless, the predicted cassava yields were reasonably higher than the reported yields of average farmer under rainfed conditions.

SUMMARY AND CONCLUSIONS

The objective of this study was to determine alternative production activities through yield prediction of several crops under a combined use of organic and inorganic fertilizers on Oxisols and Inceptisols of eastern Rwanda and to select the best soil-fertility management options. This study was conducted with the DSSAT crop simulation models. The yields predicted by the models for a combined use of organic and inorganic fertilizers were distinctly higher than the actual yields obtained for small-scale farming in the region. Predicted crop yields for beans and groundnut did not respond to an increase in the nitrogen fertilizer level as these crops are leguminous crops and fix nitrogen. Consequently, predicted yield for these crops were appoximately the same for all the management scenarios. However, the combined use of *Tithonia diversifolia* and DAP appeared to predict higher yields for maize and sorghum, as these are cereal crops and show a significant response to an increase in nitrogen-fertilizer input. All simulated crop yields were higher on Inceptisols than on the Oxisols because of the better chemical and physical conditions of Inceptisols.

The results from the crop models showed that the prediction by DSSAT was acceptable and also realistic, although detailed experimental data were missing to verify model performance. Nevertheless, comparison of the modelling results with reported yield data revealed a satisfactory crop model performance with respect to common beans, groundnut, and maize, whereas predicted cassava yields were underestimated and predicted sorghum yields were slightly overestimated.

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