

Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferruginous tropical soil in a semi-arid region: a simulation approach

C. M. TOJO SOLER^{1,2*}, V. B. BADO³, K. TRAORE⁴, W. MCNAIR BOSTICK^{5†}, J. W. JONES⁵
AND G. HOOGENBOOM^{1,2}

¹ Department of Biological and Agricultural Engineering, The University of Georgia, Griffin, GA 30223, USA

² Current address: AgWeatherNet, Washington State University, Prosser, WA 99350, USA

³ Africa Rice Center (WARDA), 01 B.P. 2031, Cotonou, Benin

⁴ Institut de l'Environnement et de Recherches Agricoles (INERA), 04 BP:8645, Ouagadougou 04, Burkina Faso

⁵ Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL 32611, USA

(Revised MS received 19 July 2010; Accepted 13 October 2010; First published online 28 January 2011)

SUMMARY

In recent years, simulation models have been used as a complementary tool for research and for quantifying soil carbon sequestration under widely varying conditions. This has improved the understanding and prediction of soil organic carbon (SOC) dynamics and crop yield responses to soil and climate conditions and crop management scenarios. The goal of the present study was to estimate the changes in SOC for different cropping systems in West Africa using a simulation model. A crop rotation experiment conducted in Farakô-Ba, Burkina Faso was used to evaluate the performance of the cropping system model (CSM) of the Decision Support System for Agrotechnology Transfer (DSSAT) for simulating yield of different crops. Eight crop rotations that included cotton, sorghum, peanut, maize and fallow, and three different management scenarios, one without N (control), one with chemical fertilizer (N) and one with manure applications, were studied. The CSM was able to simulate the yield trends of various crops, with inconsistencies for a few years. The simulated SOC increased slightly across the years for the sorghum–fallow rotation with manure application. However, SOC decreased for all other rotations except for the continuous fallow (native grassland), in which the SOC remained stable. The model simulated SOC for the continuous fallow system with a high degree of accuracy normalized root mean square error (RMSE) = 0.001, while for the other crop rotations the simulated SOC values were generally within the standard deviation (s.d.) range of the observed data. The crop rotations that included a supplemental N-fertilizer or manure application showed an increase in the average simulated aboveground biomass for all crops. The incorporation of this biomass into the soil after harvest reduced the loss of SOC. In the present study, the observed SOC data were used for characterization of production systems with different SOC dynamics. Following careful evaluation of the CSM with observed soil organic matter (SOM) data similar to the study presented here, there are many opportunities for the application of the CSM for carbon sequestration and resource management in Sub-Saharan Africa.

INTRODUCTION

Several studies have shown that soils in West Africa are structurally degraded and that the nutrients are

depleted (Pichot *et al.* 1981; Bado *et al.* 1997; de Ridder *et al.* 2004; Schlecht *et al.* 2007). Furthermore, agricultural systems and farming techniques contribute to the degradation of environmental resources (Bandre & Batta 1998). In recent years, interest in the sequestration and turnover of organic matter (OM) in soils has increased because soil organic matter (SOM) affects the stabilization of soil structure and the

* To whom all correspondence should be addressed.

Email: cecilia.tojosoler@wsu.edu

† In memoriam.

cycling of organically held plant nutrients (Oades & Waters 1991; Tiessen *et al.* 1994; Lal *et al.* 2007). In addition, carbon (C) held in or released from SOM could change atmospheric carbon dioxide (CO₂) levels (Schlesinger 1991; Reeves 1997; Tiessen *et al.* 1998). The exchange of C between the land surface and the atmosphere is responsible for a large fraction of the global variation in atmospheric CO₂, both within and between years (Tucker *et al.* 1986). Changes in vegetation productivity and C storage due to climate change and change in land use could have an important impact on the global C cycle (Mooney & Koch 1994).

Sorghum (*Sorghum bicolor*) is the main cereal crop in West Africa. Cotton (*Gossypium* spp.) is considered to be more profitable economically and plays an important role in Burkina Faso's economy, but can only be grown in areas where there is sufficient rainfall. Peanut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) are the most commonly grown legumes (Bado 2002). In many cases, food crops are grown as dual purpose crops in which the seeds are used for human consumption, whereas the stover is used for feeding animals. Bado (2002) reported that rotations with peanut or cowpea increased the amount of available nitrogen (N) for the next crop, resulting in a considerable increase in sorghum yield. Short-term use of chemical fertilizer, followed by maintenance fertilization using chemical and animal manure, are required to improve soil fertility and increase productivity, but in some cases socio-economic constraints have largely prevented the improvement of most semi-arid agricultural systems to date (Tiessen *et al.* 1998; Bationo *et al.* 2007; Doraiswamy *et al.* 2007).

Bado *et al.* (2006b) emphasized the importance of identifying a cost-effective way of improving soil fertility and productivity in Burkina Faso and other countries in Sub-Saharan Africa. In a crop rotation study conducted in Burkina Faso, Bado *et al.* (2006b) found that high yields were achieved by simultaneous application of organic and mineral fertilizers or when mineral fertilizers were associated with dolomite. Nitrogen fixing legumes, such as peanut and cowpea, are important components of the cropping system of resource-poor farmers and serve as food as well as cash crops (Bado *et al.* 2006a). Crop rotations of continuous sorghum and cotton-peanut-sorghum resulted in a decrease in soil organic carbon (SOC). Low quantities of manure, e.g. 5 tonnes(t)/ha every 2 years, did not significantly increase SOC after 6 years of cultivation. Ouédraogo *et al.* (2006) reported that combining recalcitrant organic amendments and N fertilizer is the best option in sustaining crop production in semi-arid West Africa due to a positive change in soil particulate OM and a reduction in the decline of soil C, especially for the more stable fraction that is responsible for the soil structure maintenance. Hien *et al.* (2006) recommended selection of crops with a

good rooting system, the application of organic manures, which are resistant to rapid biodegradation, reduction of tillage to avoid creating conditions for rapid biodegradation and regular liming in order to reduce the loss of soil C. A long-term rotation study was conducted from 1960 to 1978 in a degraded ferruginous tropical soil of Burkina Faso: soil C was measured in 1969 and 1978 and it was found that the soil C in the 0–200 mm layer decreased from 2.9 to 2.5 g/kg for the control treatment without fertilizers, from 2.9 to 2.4 g/kg for the treatment with applications of inorganic fertilizers and from 3.1 to 2.5 g/kg for the treatment with inorganic fertilizers and crop residues (sorghum) incorporated into the soil. The soil C increased from 3.1 to 3.5 g/kg for the treatment with inorganic fertilizers and 5 t/ha/yr of manure and increased from 5.3 to 6.6 g/kg for the treatment with inorganic fertilizers and 40 t/ha/yr of manure (Pichot *et al.* 1981). Lal (2000) observed annual rates of soil C increase under no-till management ranging from 363 kg/ha/yr to more than 1000 kg/ha/yr (for one severely depleted soil) over a 3-year experiment to restore soil C in western Nigeria.

In other regions, such as India, it was found that the total system productivity was greater in groundnut-groundnut and groundnut-chickpea systems in comparison with other systems, but the SOC declined (Ghosh *et al.* 2006). In a study conducted in Spain, Herencia *et al.* (2008) reported that in general, treatments with manure resulted in increased soil nutrient values, which had an effect on several later crop cycles, and that the use of organic composts resulted in an increase in SOC and the storage of nutrients, which can provide long-term fertility benefits.

However, soils, climate and management practices vary over space and time, creating an almost infinite combination of factors that interact and influence how much C is stored in soils. Quantifying soil C sequestration under widely varying conditions is complicated. Thus, simulation models can be used to complement information gained from experiments to help understand and predict SOC and yield responses to soil, climate and crop management. Typically, long-term effects can be assessed by the models to predict environmental risks and to evaluate alternative management practices for alleviating these risks (Muchow *et al.* 1991; Thornton *et al.* 1995; Chipanshi *et al.* 1997; Nijbroek *et al.* 2003). The Decision Support System for Agrotechnology Transfer (DSSAT) is a comprehensive decision support system (DSS) for assessing management options (Tsuji *et al.* 1994; Jones *et al.* 2003; Hoogenboom *et al.* 2004). The cropping system simulation model (CSM) included in DSSAT v4.0 (Jones *et al.* 2003; Hoogenboom *et al.* 2004), is process-oriented, dynamic and simulates growth, development and yield for more than 25 different crops. The Century model (Parton *et al.* 1993) simulates the long-term dynamics of C for different

Table 1. Crops planted by year for the different crop rotations

| Year | Crop rotations | | | | | | | |
|------|-----------------|----------------|-----------------------|-----------------------|---------------|----------------------|---------------|---------------|
| | Sorghum–sorghum | Sorghum–fallow | Peanut–sorghum–cotton | Peanut–cotton–sorghum | Cotton–cotton | Cotton–maize–sorghum | Peanut–peanut | Fallow–fallow |
| 1993 | Sorghum | Sorghum | Peanut | Peanut | | | Peanut | Fallow |
| 1994 | Sorghum | Fallow | Sorghum | Cotton | | Maize | Peanut | Fallow |
| 1995 | Sorghum | Sorghum | Cotton | Sorghum | | Sorghum | Peanut | Fallow |
| 1996 | Sorghum | Fallow | Peanut | Peanut | | Cotton | Peanut | Fallow |
| 1997 | Sorghum | Sorghum | Sorghum | Cotton | | Maize | Peanut | Fallow |
| 1998 | Sorghum | Fallow | Cotton | Sorghum | | Cotton | Peanut | Fallow |
| 1999 | Sorghum | Sorghum | Peanut | Peanut | | Cotton | Peanut | Fallow |
| 2000 | Sorghum | Fallow | Sorghum | Cotton | | Maize | Peanut | Fallow |
| 2001 | Sorghum | Sorghum | Cotton | Sorghum | Cotton | Sorghum | Peanut | Fallow |
| 2002 | Sorghum | Fallow | Peanut | Peanut | Cotton | Cotton | Peanut | Fallow |
| 2003 | Sorghum | Sorghum | Sorghum | Cotton | Cotton | Maize | Peanut | Fallow |
| 2004 | Sorghum | Fallow | Cotton | Sorghum | Cotton | Sorghum | Peanut | Fallow |

plant–soil systems. It was developed to analyse a wide range of crop rotations and tillage practices and to determine the impact of crop management on the productivity and sustainability of agroecosystems. The Century model has been used successfully to simulate SOC across a variety of land uses and climate types (Kelly *et al.* 1997; Diagana *et al.* 2007; Ogle *et al.* 2007). Gijsman *et al.* (2002) incorporated a Century-based module into CSM to allow for more flexibility in handling different agricultural systems for long-term simulations of crop rotations. This capability is particularly important to enable CSM to be used for predicting yields in low-input cropping systems where soils tend to be deficient in OM and nutrients. However, even under high-input management systems where large amounts of soluble nutrients are supplied, hence, minimizing the role of OM in supplying nutrients, its role in enhancing soil productivity via the modification of soil processes cannot be overlooked (Porter *et al.* 2010).

There are a number of uncertainties associated with simulation models and their use, and if one does not adequately address these uncertainties, the simulated results will be meaningless (Jones *et al.* 2004). These uncertainties are due to the fact that models are simplifications of reality; there are uncertainties in model parameters and in the data inputs. Thus, research is needed to ensure that models can reproduce the responses that are observed in field experiments. However, soil C measurements are also uncertain and costly, and the errors could be much larger than the annual changes in SOC. By combining measurements with model predictions, a more accurate estimate of SOC can be obtained (Koo *et al.* 2003). The goal of the present study was to determine the yield variability and SOC dynamics for different rotations and

fertilizer levels of cropping systems in a semi-arid region of West Africa. Specific objectives included the simulation of eight crop rotations and three fertilizer treatments, and the analysis of observed and simulated yield trends and SOC dynamics for the different crop rotations and management treatments.

MATERIALS AND METHODS

Crop management

A crop rotation study was initiated in Farakô-ba (4°20'W, 11°6'N), Burkina Faso in 1993 (Bado 2002). The rotations consisted of various cropping sequences that included sorghum, cotton, peanut and maize, which are important food and cash crops in the region, and native grassland as a fallow. The experiment was initiated on a 6-year native grassland fallow and was an incomplete-factorial, split-plot design arranged in randomized blocks with eight crop rotations as whole plot factors, nine input levels as split-plot factors and four replications. The input levels were distinguished by the type of soil amendment that was added (Bado 2002; Bostick *et al.* 2007).

The eight rotations plus three management treatments were analysed from 1993 to 2004 (Table 1). The crop rotations were: (1) continuous fallow, (2) continuous sorghum, (3) continuous peanut, (4) continuous cotton, (5) peanut–cotton–sorghum, (6) peanut–sorghum–cotton, (7) maize–sorghum–cotton and (8) sorghum–fallow. The three management treatments were: (1) no supplemental N fertilizer (control treatment), (2) the application of inorganic N and (3) the application of manure. The recommended application rates of inorganic N, P and K prior to planting were 37, 10 and 11 kg/ha, respectively, for sorghum; 44,

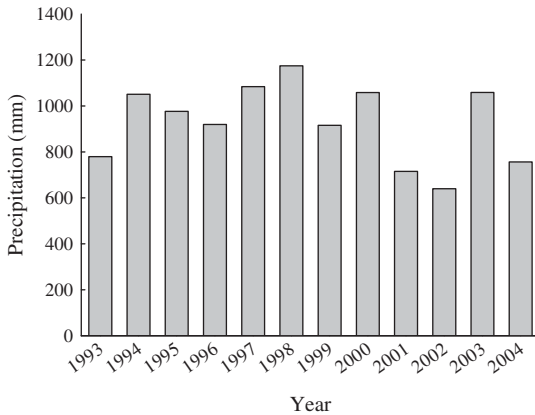


Fig. 1. Total precipitation for the cropping season (May–October) in Farakô-ba, Burkina Faso.

15 and 17 kg/ha, respectively, for cotton; 14, 10 and 11 kg/ha, respectively, for peanut and 60, 12 and 7 kg/ha, respectively, for maize. For the manure treatments, air-dried cow manure (184 g C/kg, 18 g N/kg, 3.1 g P/kg and 1.6 g K/kg) at a rate of 3000 kg/ha was applied each year at planting.

Climate

The climate of Burkina Faso is similar to other countries in the region and is characterized by a dry season, which lasts, on average, from mid-November to mid-April, and a wet season, which lasts from May to mid-September. Most of the country (centre and south) lies in the Sudanese climatic zone, while the north is influenced by the climate of the Sahel. Rainfall varies from 400 mm in the north to 1000 mm in the southwest. However, the most important aspects of the rainfall are its temporal and spatial variability (Bandre & Batta 1998).

According to the FAO eco-climatic classification, Farako-bâ is located in the Sudanian climatic zone, defined by one rainy season per year (FAO 2005). The average seasonal cumulative precipitation and s.d. from May to October from 1993 to 2004 at the study site were 927 and 171 mm, respectively. The total precipitation for the cropping season (May–October) was variable for each individual year (Fig. 1). The maximum total seasonal rainfall was 1174 mm for 1998 and the minimum was 639 mm for 2002. The cropping season is also characterized by high temperatures. For example, the average maximum and minimum temperatures for June were 32 and 22.3 °C, respectively, while for July they were 30 and 21.5 °C, respectively. However, the highest temperatures usually occur during the months of March and April, with average maximum temperature of 38 °C.

Soil characteristics and measurements

The soil at the experimental site was a weathered ferruginous tropical soil (Bado 2002), which is an Alfisol or Ultisol in the USDA soil taxonomy classification (Soil Survey Staff 1999). This soil covers 0.40 of the land area in the sub-humid zone of West Africa (6–12°N; Adeoye & Mohamed-Saleem 1990). These ferruginous tropical soils are characterized by a sandy surface horizon that is low in OM and base exchange capacity (ILCA 1979). The soil texture at the experimental site was loamy sandy, with sand, silt and clay contents of 74, 19 and 7% by volume, respectively (Bado 2002; Bostick *et al.* 2007). The soil profile inputs were complemented with data from a ferruginous tropical soil from northern Ghana that was obtained from DSSAT V4.0 database (Gijssman *et al.* 2007). The next soil horizon used as input for the model was similar to the upper horizon in terms of texture, and was characterized by sand, silt and clay contents of 66, 21 and 13% by volume, respectively (0.2–0.40 m depth). The next soil horizon, 0.4–1.2 m depth, contained 55, 22 and 23% by volume of sand, silt and clay, respectively. The bulk density in the top 0.2 m of the soil was estimated as 1.46 g/cm³ from soil texture components (Rawls 1983). This top layer of the soil had low values for total OM (11 g/kg), a weak cation exchange capacity (CEC), was slightly acidic (pH water = 6.5) and was N and P poor (Bado 2002).

Three composite samples were collected from the top 0.2 m of soil before planting in 1993 to characterize the initial SOC of the native grassland. The average SOC was 5.5 g/kg. SOC was also measured after harvest in 1998 and 2003 for some crop rotations only (continuous fallow, continuous sorghum, sorghum–fallow, continuous cotton and maize–sorghum–cotton) and input levels (control, N-fertilizer and manure applications). The Walkley–Black method (Walkley & Black 1934) was used for all SOC determinations. For the 1998 and 2003 SOC measurements, four composite soil samples were taken and analysed for each treatment that was measured.

Simulation of crop rotations

The crop rotation or sequence tool of CSM-DSSAT V4.0 (Thornton *et al.* 1995) was used to simulate the eight crop rotations and three fertilizer treatments. The CSM-DSSAT sequence analysis tool allows the user to conduct simulations of crop rotations or crop sequences and to analyse the results (Bowen *et al.* 1998). The main aspect of the sequence analysis is the consideration of experiments that are conducted across multiple cropping seasons. Therefore, the carry-over of the soil water and nutrient status is affected from one cropping season or crop to the subsequent one (Thornton *et al.* 1994). The Century soil OM module is integrated into the CSM-DSSAT

V4.0 in order to better model the dynamics of soil organic nutrient processes (Gijssman *et al.* 2002; Porter *et al.* 2010). The current version of CSM does not consider the P and K balance in the soil (Jones *et al.* 2003); thus, these elements were not defined as inputs.

Daily rainfall data were obtained from a conventional weather station located at the research station of the Environmental and Agricultural Research Institute (INERA), located adjacent to the experimental site, in Farakô-ba. The daily maximum and minimum temperature and solar radiation were obtained from the nearest weather station (10 km), located in Bobo Dioulasso. Using weather data from these two stations was the best way to obtain accurate daily temperatures and also rainfall at the experimental site.

The soil parameters needed to characterize the profile were obtained from Bado (2002). The parameters related to the different SOC decomposition rates that were required to run the Century component of the CSM were set according to previous reports on similar soils from Burkina Faso (Hien *et al.* 2006; Barthes *et al.* 2008). Therefore, the SOC corresponding with the fraction of stable organic C (SOM3, also called passive) was set equal to 0.26. Hien *et al.* (2006) reported 2.6 g/kg of SOC for a soil in the Savannah region of the Southwest of Burkina Faso after 13 years of continuous cropping, with removal of the crop residues. The intermediate SOC (SOM2) was set equal to 0.72. The model was set up to initiate the simulations 6 years prior to the beginning of the experiment. During this period, the growth of a native grassland fallow was simulated, mimicking the same crop that was grown prior to the start of the rotation experiment. Thereafter, the eight rotations and the three management treatments were simulated from 1993 to 2004 (Table 1).

For model evaluation, the simulated dates of flowering and maturity as well as yield were compared with the observed values. The phenology was evaluated using growth and development data for 2004 (data not shown). The cultivar coefficients are specific for each crop, and were obtained sequentially, starting with the phenological development parameters related to flowering and maturity dates, followed by the crop growth parameters related with kernel filling rate and kernels number per plant (Hunt & Boote 1998). An iterative procedure (Hunt *et al.* 1993) was used to select the most appropriate value for each coefficient. A detailed description of the cultivar coefficients used by the CSM-DSSAT V4.0 can be found in Hoogenboom *et al.* (1994) and Hunt & Boote (1998). The combination of cultivar coefficients that resulted in an average simulated yield that was the most similar to the average observed yield was selected. The selected varieties used in the present study were: Sarioso-02 for sorghum, RMP12 for peanut, FK37 for cotton and SR22 for maize.

Statistical analysis

An analysis of yield variability, total biomass incorporated into the soil and SOC was conducted for the different crop rotations and fertilizer treatment combinations. The observed and simulated yield variations were examined by plotting the normalized yield for each crop in each rotation and treatment according to Meinke & Hammer (1995).

$$Y_n = (Y_i - \bar{Y})/S.D. \quad (1)$$

where Y_n is the normalized yield, Y_i is the yield for each individual growing season, \bar{Y} is the average yield for each crop across all years of the rotation and s.d. is the standard deviation of the yield for each crop across all years of the rotation.

For the simulated yield, an analysis of the trends was conducted for the different rotations. The results were examined by plotting the progression with time of the cumulative deviations from the mean for the different crops of the different rotations and treatments. The plots start and end with zero, and the year to year fluctuations correspond to periods above or below the average yield for different crops. In the present study, the plots show long-term yield trends for different crops without removing variability (Russell 1981; Hammer *et al.* 1987; Meinke & Hammer 1995; Garcia *et al.* 2006). For the simulated SOC dynamic, an analysis of the different rotations and treatments was conducted, which was presented in a graphical format depicting also the observed average and s.d. of the SOC values for the top soil layer (0–0.2 m) for 1993, 1998 and 2003.

RESULTS

Yield

The crop rotation or sequence tool of DSSAT V4.0 was able to simulate the observed yields for different crop rotations (Table 2). The average observed yields varied between 720 kg/ha for the continuous sorghum rotation and 2005 kg/ha for maize crop in the cotton–maize–sorghum rotation. The simulated average yields varied between 801 kg/ha for the continuous cotton rotation and 2672 kg/ha for the maize crop in the cotton–maize–sorghum rotation. The Pearson coefficient between observed and simulated yield values was 0.84 and the root mean square error (RMSE, expressed as a proportion) was 0.26 indicating a fairly good simulation. The variation in the simulated yield was similar to the variation of the observed yield for all crop rotations and the three treatments (Figs 2–4). There were a few anomalies in which the simulated variation in yield differed from the observed, e.g. in 1993 the models in general under-predicted the yield. The differences between simulated and observed values were partially due to the fact that the models

Table 2. Observed and simulated average yields for different crop rotations

| Crop rotation | Crop | Observed yield (kg/ha) | Simulated yield (kg/ha) | Statistics |
|-----------------------|---------|------------------------|-------------------------|------------|
| Sorghum–sorghum | Sorghum | 720 | 875 | |
| Fallow–sorghum | Sorghum | 1179 | 973 | |
| Peanut–sorghum–cotton | Peanut | 919 | 830 | |
| | Sorghum | 1183 | 907 | |
| Peanut–cotton–sorghum | Cotton | 898 | 1077 | |
| | peanut | 929 | 978 | |
| | Cotton | 845 | 1268 | |
| Cotton–cotton | Sorghum | 1112 | 882 | |
| | Cotton | 880 | 801 | |
| Cotton–maize–sorghum | Cotton | 1138 | 1091 | |
| | Maize | 2005 | 2672 | |
| | Sorghum | 1059 | 839 | |
| Peanut–peanut | Peanut | 1128 | 887 | |
| Average | | 1077 | 1083 | |
| RMSE (proportion) | | | | 0.26 |
| Pearson coefficient | | | | 0.84 |

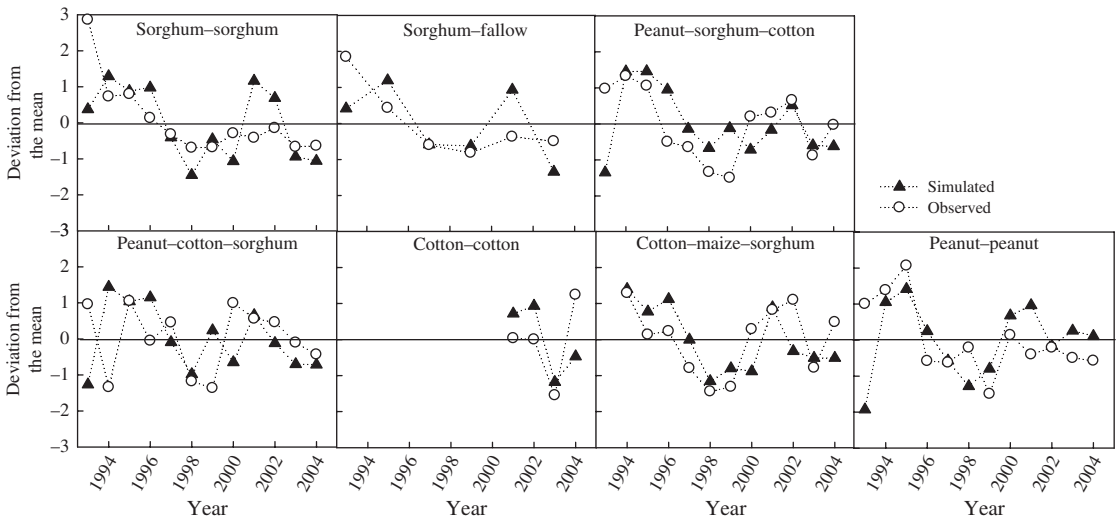


Fig. 2. Simulated and observed yield expressed as s.d. from the mean for the different rotations without N fertilizer (control).

do not consider all biotic and abiotic factors that impact crop growth and development. Differences between observed and simulated values were probably due to pest and diseases, but there were no detailed experimental records to support this on particular years and crops. In general, the observed yields were higher than the average only at the beginning of the cropping system rotations. This can be explained by the better soil properties for the first year of the rotations, which were favoured by the 6 previous years with native grassland. However, for the remainder of the years for the different rotations, the variation in the simulated yield was, in general, similar to the

observed yield. Lack of agreement between observed and simulated accumulated deviations occurred in the control treatments for the continuous sorghum and sorghum–fallow rotations in 2001, in which the observed yields were below the average, but the simulated yield values were above average (Fig. 2). For the peanut–cotton–sorghum rotation without N fertilizer (control), the simulated peanut yield for 1996 and 2002 were below the average simulated, while the observed yields were above the average simulated, while the observed yields were above the average observed. In 1999, the opposite occurred; the simulated yield was above the average and the observed yield was below average. These examples indicate that the model was

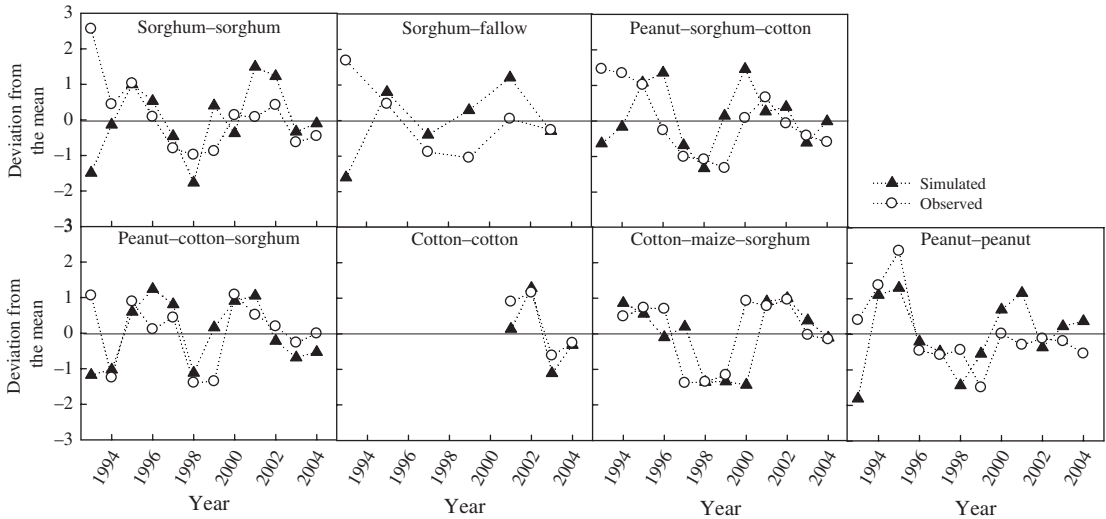


Fig. 3. Simulated and observed yield expressed as s.d. from the mean for the different rotations with N fertilizer.

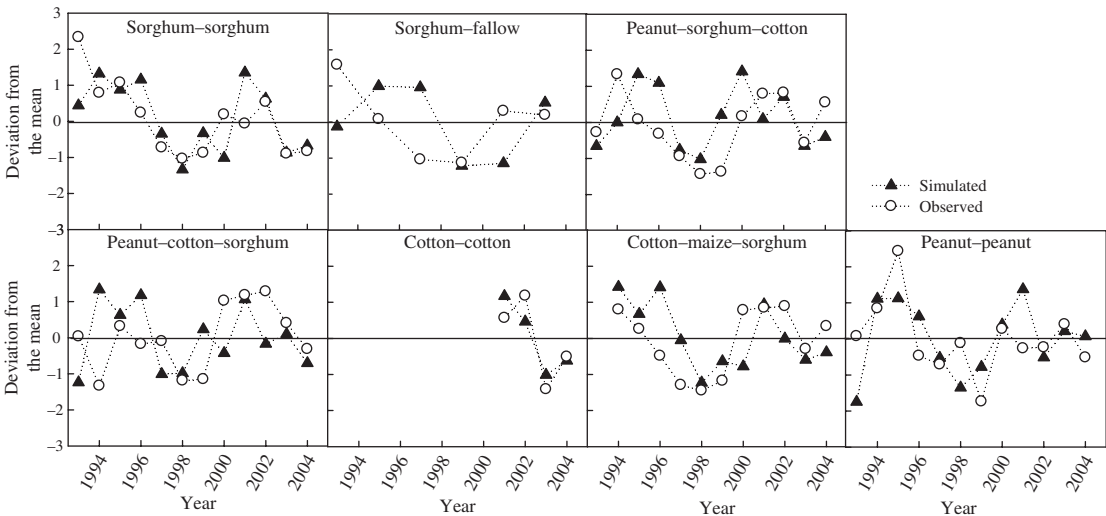


Fig. 4. Simulated and observed yield expressed as s.d. from the mean for the different rotations with manure applications.

unable to simulate yield trends accurately for a few specific years for the control rotation (without N). Similar to these specific circumstances, there were also a few predictions in simulated yield trends that were different from observed for specific cases for crop rotations with N fertilizer and with manure applications. This included the peanut-cotton-sorghum rotation with N fertilizer and also the rotation with manure applications for 1999 where the observed peanut yield was below the average, while the simulated yield was above the average (Figs 3 and 4).

The progression across years of the cumulative deviations from the mean for the different crops of the

various rotations and treatments were plotted for simulated and observed yield (Figs 5–7). The plots start and end with zero, and the year to year fluctuations correspond to periods above or below the average yield. Thus, the yield trends expressed as the cumulative deviation from the mean yield for each crop of a rotation and treatment had, for most of the years, crops and treatments, a good agreement between the simulated and observed values (Figs 5–7). There was a decrease in observed yield for the final years of the crop rotations (2002–4), with a below-average yield for the different crops. In general, the decrease in yield for the final years of the rotation was

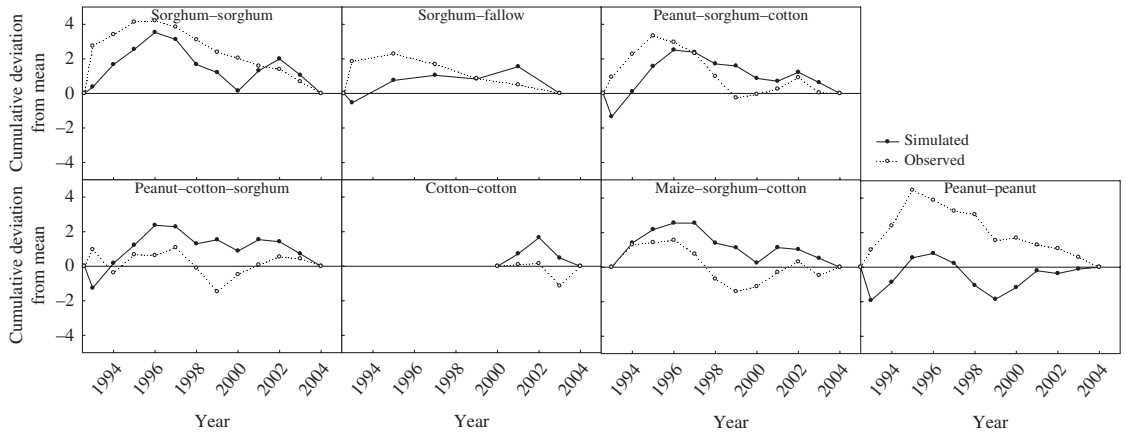


Fig. 5. Simulated and observed yield expressed as cumulative deviation from the mean (cumulative normalized yield) for the different rotations without N fertilizer (control).

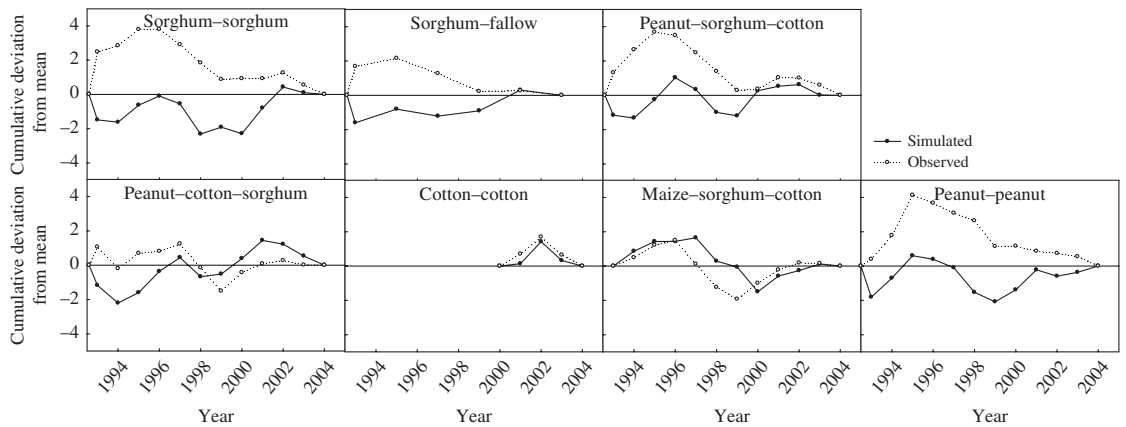


Fig. 6. Simulated and observed yield expressed as cumulative deviation from the mean (cumulative normalized yield) for the different rotations with N fertilizer.

also simulated. The yield decrease can be explained by the reduction in soil fertility after years of continuous cropping systems.

Biomass

For the crop rotations involving N fertilizer and manure applications, the simulated average biomass and s.d. varied among rotations and crops. However, this variation was similar between N fertilized treatments and manure applied treatments, as represented in the average and s.d. bars of Fig. 8. When comparing average biomass values it was found that peanut was the crop with the largest simulated biomass values. The growing conditions were better for peanut because it is a legume and can fix N from the rhizobia that are formed in the root nodules. Sorghum

was affected by N stress even when N was applied, because the amount was insufficient to supply the N needed by the crop. In the maize-sorghum-cotton rotation, the sorghum biomass with N fertilizers was lower than sorghum in the same sequence with manure. The manure applied increased the N available in the soil and this explains the high average values of biomass in comparison to the N fertilizer treatment. The aboveground biomass for the crop rotations without fertilizer (control) was removed from the experimental plot at harvest and not incorporated into the soil, causing a reduction in SOC across years.

SOC

Both the observed and simulated SOC content for all crop rotations decreased across the years of the

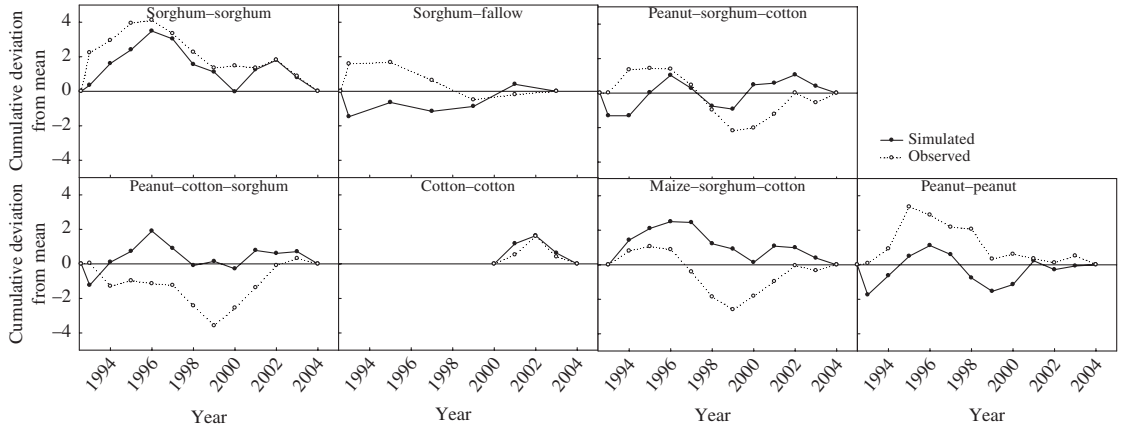


Fig. 7. Simulated and observed yield expressed as cumulative deviation from the mean (cumulative normalized yield) for the different rotations with manure applications.

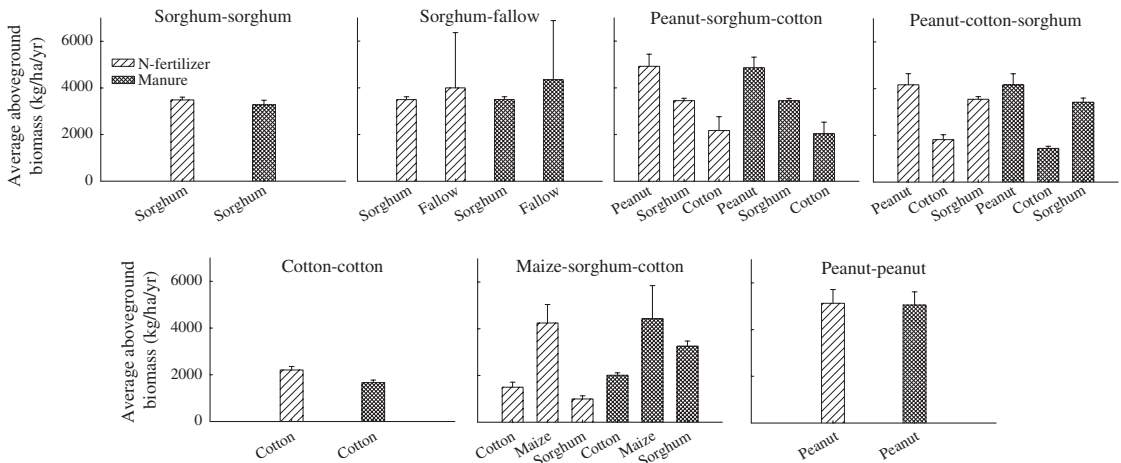


Fig. 8. Simulated average aboveground biomass incorporated into the soil for the different rotations with N fertilizer and manure applications.

experiment, except for the continuous fallow (native grassland) in which the SOC remained stable around 5.0–5.5 g/kg (Fig. 9) and the sorghum–fallow rotation with manure application. The crop rotation or sequence tool of CSM-DSSAT V4.0 (and the integrated Century SOM module) was able to simulate the SOC for the continuous fallow system accurately, with a value of 0.01 for the normalized RMSE (expressed as a proportion). In general, the simulated SOC values were within the range of the s.d. of the observed data for the other crop rotations (Fig. 9). The observed SOC rate of decline in the rotations sorghum–fallow, continuous sorghum and continuous cotton appeared to stabilize after 1999, but with an important variability in the SOC values. The model predicted a

continued reduction in SOC rate of decline that eventually could impact the sequestration of SOC estimations. The simulated biomass that was incorporated into the soil for the N fertilized treatments and manure treatments resulted in a less pronounced decrease of simulated SOC across the years (Fig. 8).

The crop rotation that had the best performance with respect to simulated SOC was the sorghum–fallow rotation with manure application because this rotation had an average increase of 31 kg/ha/yr for the top 0.2 m of the soil profile (Fig. 10). The same crop rotation showed smaller decreases in SOC for the N fertilizer application and for the treatment that did not have any fertilizer application in comparison with the other crop rotations. The decrease in simulated SOC

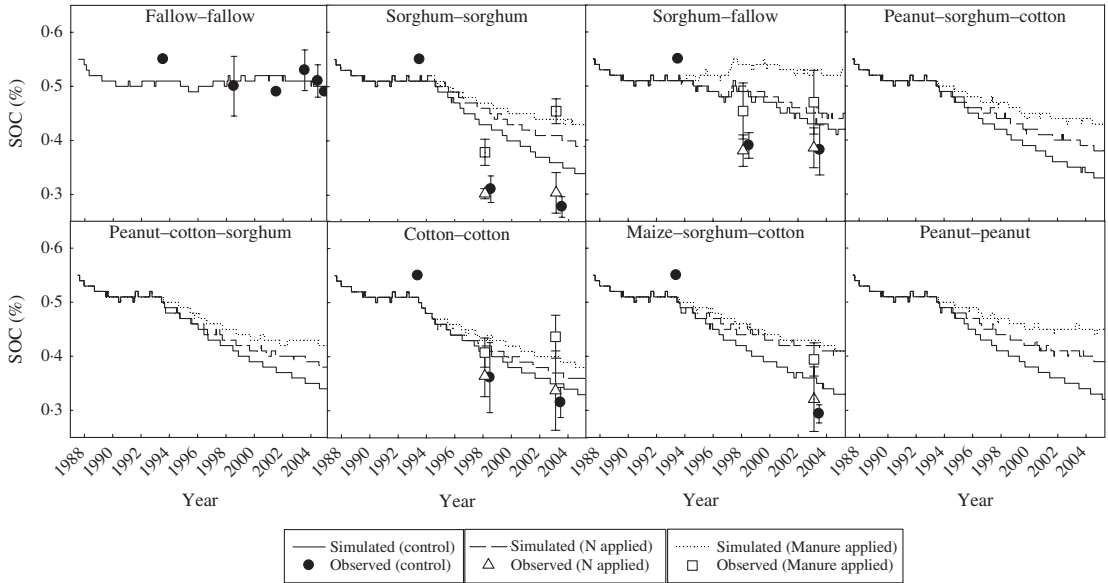


Fig. 9. Simulated and observed SOC for the different crop rotations and different managements.

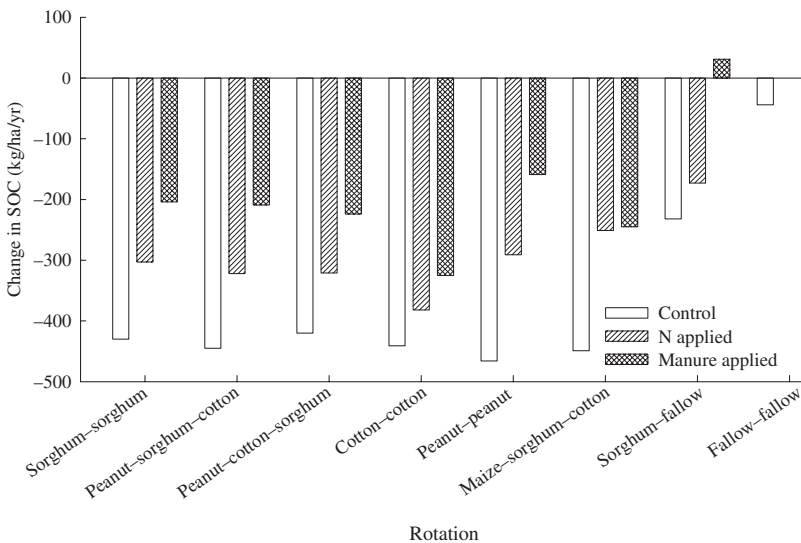


Fig. 10. Simulated average SOC change per year (0–0.2 m depth) for different rotations and management practices from 1993 to 2004.

was 173 kg/ha/yr for the N fertilizer application treatments and 232 kg/ha/yr for treatments that did not have any fertilizer. Decreases in SOC of more than 400 kg/ha/yr were simulated for each of the other control crop rotations (treatments without fertilizer application) (Fig. 10). When N fertilizer was applied, the model simulated a decrease in SOC that ranged from 250 to 380 kg/ha/yr. When manure was applied,

the model simulated a decrease in SOC decrease that ranged from 160 to 325 kg/ha/yr for the top 0.2 m of the soil, for continuous peanut and continuous cotton rotations, respectively.

In cropping systems with limited amounts of external inputs, the SOM pool may contribute significantly to plant nutrition (Vanlauwe *et al.* 1998). The Century model includes three SOM pools, active

Table 3. Simulated average SOC for the three components SOM1 (microbial), SOM2 (intermediate) and SOM3 (passive) for all treatments at a depth of 0–0.2 m for 2004 after 11 years of crop rotation simulation

| | SOM 1 (kg/ha) | SOM 2 (kg/ha) | SOM 3 (kg/ha) | Total SOM (kg/ha) |
|---------------------|-----------------------|-----------------------|-----------------------|-------------------|
| Control (without N) | 154 | 6018 | 2836 | 9008 |
| Nitrogen fertilizer | 341 | 6919 | 2867 | 10 127 |
| Manure application | 268 | 8185 | 2863 | 11 316 |
| | SOM 1 (proportion) | SOM 2 (proportion) | SOM 3 (proportion) | |
| Control (without N) | 0.02 | 0.67 | 0.32 | |
| Nitrogen fertilizer | 0.03 | 0.68 | 0.28 | |
| Manure application | 0.02 | 0.72 | 0.26 | |

(microbial SOM1), slow (intermediate SOM2) and passive (SOM3), which have different potential decomposition rates (Parton *et al.* 1993; Batjes 2001). At the end of crop rotation in 2004, the simulated average values for the different components of the SOC was high for the SOM2 fraction (intermediate) for the treatments with manure applied, accounting for 0.72 of the total (Table 3). On the other hand, the control crop rotations (without N applied) had the lowest values of SOM2 in year 2004. When analysing the SOC dynamic for each rotation, it was found that the continuous fallow (native grassland) had a high simulated SOM2 in year 2004 of 0.75. For the crop rotations without N fertilizer (control), the SOC decreased to near 0.003 after 12 years.

DISCUSSION

The removal of aboveground biomass at harvest for the crop rotations without fertilizer (control) caused an average reduction in SOC of 46% after 12 years, as there was no incorporation of biomass and residue into the soil. The removal of crop residues has been reported to be adverse in terms of soil quality due to the depletion of the soil C pool, which negatively affects crop production (Lal 2007). In a study conducted in Ghana, Adiku *et al.* (2009) found that over a 4-year period, maize rotated with bare fallow produced an average maize biomass and yield of 4.0 and 1.0 t/ha/yr, respectively; SOC declined over time, with the maize bare fallow rotation losing about 55% of the initial SOC in the 4 years. The decline in SOC was 19% for a fertilized maize–grass rotation, and other treatments lost between 33 and 44% of the initial SOC. Furthermore, results from Zimbabwe reported by Mtambanengwe & Mapfumo (2005) highlight that the cumulative effects of applying substantial amounts of OM to specific areas on a regular basis resulted in consistently higher levels of SOC in designated rich fields than corresponding poor fields (or field sections). The key challenge is enabling farmers to generate sufficient quantities of biomass during each

cropping cycle in order to maintain the productivity of rich fields, while rehabilitating the non-productive ones (Mtambanengwe & Mapfumo 2005). Crop residues also have been reported to be a major factor in maintaining or reducing the loss of SOC on two tropical soils of Brazil (Leite *et al.* 2009). Nziguheba *et al.* (2005) found in western Kenya that organic residues can contribute to the improvement of soil nutrient cycling. However, the magnitude of their contribution depends on the biochemical properties of the residues. Regular applications of manure on rice–wheat and maize rotation also have been associated with an increase in SOC and grain yield across sites in China (Zhang *et al.* 2009).

Zingore *et al.* (2005) reported that for soils on smallholdings in Zimbabwe, the organic C declined rapidly under cultivation to attain a new equilibrium within 10 years after woodland clearance. Mando *et al.* (2005) found that 10 years of continuous sorghum cultivation without organic inputs in a sandy loam Lixisol soil at Saria, Burkina Faso caused significant losses of C. However, addition of manure was effective in maintaining similar levels of C compared to fallow plots. Without manure, SOM was mainly stored as fine organic matter (FOM) with a size-fraction <0.053 mm. In plots with manure and in fallow plots, the addition of manure doubled the particulate organic matter (POM) (size-fraction 0.053–2 mm) concentration. POM was greatly affected by long-term soil management options. Similar results were also found by Nziguheba *et al.* (2005) in a soil amended with organic residues in western Kenya and by Ouattara *et al.* (2006) in western soils of Burkina Faso. Willson *et al.* (2001) reported that the POM amount combined with information about recently incorporated crop residues, were found to be good predictors of N mineralization potential in systems using conventional, legume-based organic and manure-based organic fertility management. In a study conducted in West Africa, Vanlauwe *et al.* (1998) found that the average proportion of soil N belonging to the POM pool ranged from 0.09 to 0.29 depending

on the annual N inputs from maize stover and prunings. Bationo & Buerkert (2001) recommended targeted applications of mineral fertilizers and effective recycling of organic amendments as crop residues and manure to maintain food production for a rapidly growing population in the agro-pastoral farming systems in the Sudano–Sahelian zone of West Africa. Similarly, Vågen *et al.* (2005) and Farage *et al.* (2007) stated that for croplands the critical issue in increasing SOC is the addition of crop residues or manure and the reduction in soil disturbance through conservation tillage or no-till systems. De Costa & Sangakkara (2006) highlighted the benefits of agronomic measures such as mulching, the application of green manure, the use of crop residues, fallow rotation and agroforestry as very economical and efficient methods of increasing productivity and maintaining sustainability of small farming units in Asia. Zougmore (2003) recommended combining soil and water conservation techniques with soil fertility management practices to improve the efficiency of these measures, and thus sustain soil productivity in Burkina Faso and other countries in Sub-Saharan Africa.

In the present study, the model simulated the SOC for the continuous fallow system accurately, with a normalized RMSE (expressed as a proportion) of 0.001. In general, the simulated SOC values were within the range of the s.d. of the observed data for the other crop rotations. The simulated results for SOC from the present study are similar to previous studies that were conducted with the standalone version of the Century model. For instance, the Century model was able to accurately simulate the level of total soil C for five soil types in Brazil (Cerri *et al.* 2004): modelling also provided a flexible and powerful way to assess how different scenarios for pasture management and land use change can affect soil C dynamics (Cerri *et al.* 2004). The present study highlights that the CSM is a useful tool to simulate crop growth and the development for various crop rotations and management practices.

The understanding of the SOC dynamic for different crop rotations is important in relation to soil fertility aspects, but it also complements the research focus in recent years on the global carbon cycle, as it has become clear that increased levels of CO₂ and other greenhouse gasses in the atmosphere are causing changes to our climate at an increasingly rapid rate

(McCarthy *et al.* 2001). Soil C sequestration has been recognized as an effective, low-cost technology to mitigate climate change. Simulation models, alone or in combination with soil sampling and other techniques, have been used to help with monitoring changes in soil carbon levels as affected by climate, soil and crop management options (Apezteguía *et al.* 2009). However, as stated by Batjes (2004), mitigation of climate change by increased C sequestration in soils appears particularly useful when addressed in combination with other pressing regional challenges that affect the livelihood of the people, such as combating land degradation and ensuring food security, while at the same time curtailing global anthropogenic emissions.

In summary, the CSM simulated the yield trends of various crops grown in Burkina Faso fairly well, with some inconsistencies for a few years. The simulated SOC increased slightly across the years for the sorghum–fallow rotation with manure application. However, the most accurate simulation of SOC was obtained for the continuous fallow (native grass) with no supplemental fertilizer applied, in which the SOC remained stable around 5.0–5.5 g/kg. The crop rotations that included N-fertilizer or manure applications showed an increase in the total amount of biomass that was simulated, which was incorporated back into the soil in order to reduce the loss of SOC. The present study showed that DSSAT and its associated CSM can be used for the identification of cropping systems that can enhance the agricultural production and sustainability in Burkina Faso and other countries in West Africa that have similarly degraded soils. However, it is very important to define the initial values for SOC accurately as this will affect the outcome of the simulations. Further research is needed in order to extend the adoption of CSMs as a tool for decision makers in Burkina Faso and other countries in the region aiming to recommend suitable rotations to different soils or environmental conditions.

This work was supported in part by a grant from the U.S. Agency for International Development through the Sustainable Agriculture and Natural Resources Management Collaborative Research Support Program (SANREM-CRSP) and by State and Federal Funds allocated to Georgia Agricultural Experiment Stations Hatch Project GEO01654.

REFERENCES

- ADEOYE, K. B. & MOHAMED-SALEEM, M. A. (1990). Comparison of effects of some tillage methods on soil physical properties and yield of maize and stylo in a degraded ferruginous tropical soil. *Soil and Tillage Research* **18**, 63–72.
- ADIKU, S. G. K., JONES, J. W., KUMAGA, F. K. & TONYIGAH, A. (2009). Effects of crop rotation and fallow residue management on maize growth, yield and soil carbon in a savannah-forest transition zone of Ghana. *e Journal of Agricultural Science, Cambridge* **147**, 313–322.
- APEZTEGUÍA, H. P., IZAURRALDE, R. C. & SERENO, C. (2009). Simulation study of soil organic matter dynamics as affected by land use and agricultural practices in semi-arid

- Cordoba, Argentina. *Soil and Tillage Research* **102**, 101–108.
- BADO, B. V. (2002). Rôle des légumineuses sur la fertilité des sols ferrugineux tropicaux des zones guinéenne et soudanaise du Burkina Faso. PhD thesis, Université Laval, Québec. (In French).
- BADO, B. V., SEDOGO, M. P., CESCAS, M. P., LOMPO, F. & BATIONO, A. (1997). Effet à long terme des fumures sur le sol et les rendements du maïs au Burkina Faso. *Cahiers Agricoles* **6**, 571–575. (In French).
- BADO, B. V., BATIONO, A. & CESCAS, M. P. (2006a). Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). *Biology and Fertility of Soils* **43**, 171–176.
- BADO, B. V., BATIONO, A., LOMPO, F., SEGDA, Z., CESCAS, M. P. & SEDOGO, M. P. (2006b). Long-term effects of cropping systems and fertilization on crop production, soil characteristics and nitrogen cycling in the Guinean and Sudanian savannah zones of Burkina Faso (West Africa). In *Management Practices for Improving Sustainable Crop Production in Tropical Acid Soils. Results of a coordinated research project organized by the Joint FAO/IAEA Programme of Nuclear Techniques in Food and Agriculture* (Eds F. Zapata & L.-M. Nguyen), pp. 47–64. IAEA Proceedings Series. Vienna: International Atomic Energy Agency.
- BANDRE, P. & BATA, F. (1998). *Soil and Water Conservation (SWC) in Burkina Faso*. National Programme for Burkina Faso. Ouagadougou, Burkina Faso: Voisins Mondiaux.
- BARTHES, B. G., BRUNET, D., HIEN, E., ENJALRIC, F., CONCHE, S., FRESCHET, G. T., D'ANNUNZIO, R. & TOUCET-LOURI, J. (2008). Determining the distributions of soil carbon and nitrogen in particle size fractions using near-infrared reflectance spectrum of bulk soil samples. *Soil Biology and Biochemistry* **40**, 1533–1537.
- BATIONO, A. & BUERKERT, A. (2001). Soil organic carbon management for sustainable land use in Sudano-Sahelian West Africa. *Nutrient Cycling in Agroecosystems* **61**, 131–142.
- BATIONO, A., KIHARA, J., VANLAUWE, B., WASWA, B. & KIMETU, J. (2007). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems* **94**, 13–25.
- BATJES, N. H. (2001). Options for increasing carbon sequestration in West African soils: an exploratory study with special focus on Senegal. *Land Degradation and Development* **12**, 131–142.
- BATJES, N. H. (2004). Estimation of soil carbon gains upon improved management within croplands and grasslands of Africa. *Environment, Development and Sustainability* **6**, 133–143.
- BOSTICK, W. M., BADO, V. B., BATIONO, A., SOLER, C. M. T., HOOGENBOOM, G. & JONES, J. W. (2007). Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso. *Soil and Tillage Research* **93**, 138–151.
- BOWEN, W. T., THORNTON, P. K. & HOOGENBOOM, G. (1998). The simulation of cropping sequences using DSSAT. In *Understanding Options for Agricultural Production* (Eds G. Y. Tsuji, G. Hoogenboom & P. K. Thornton), pp. 313–328. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- CERRI, C. E. P., CERRI, C. C., PAUSTIAN, K., BERNHOUS, M. & MELLILO, J. M. (2004). Combining soil C and N spatial variability and modeling approaches for measuring and monitoring soil carbon sequestration. *Environmental Management* **33** (Suppl. 1), S274–S288.
- CHIPANSHI, A. C., RIPLEY, E. A. & LAWFORDE, R. G. (1997). Early prediction of spring wheat yields in Saskatchewan from current and historical weather data using the CERES-Wheat model. *Agricultural and Forest Meteorology* **84**, 223–232.
- DE COSTA, W. A. J. M. & SANGAKKARA, U. R. (2006). Agronomic regeneration of soil fertility in tropical Asian smallholder uplands for sustainable food production. *Journal of Agricultural Science, Cambridge* **144**, 111–133.
- DIAGANA, B., ANTLE, J., STORVOGEL, J. & GRAY, K. (2007). Economic potential for soil carbon sequestration in the Niore region of Senegal's peanut basin. *Agricultural Systems* **94**, 26–37.
- DORAISWAMY, P. C., MCCARTY, G. W., HUNT, E. R., YOST, R. S., DOUMBIA, M. & FRANZLUEBBERS, A. J. (2007). Modeling soil carbon sequestration in agricultural lands of Mali. *Agricultural Systems* **94**, 63–74.
- FAO. (2005). *Sahel Weather and Crop Situation Report No. 2, 2005*. Rome: FAO. Available online at: <ftp://ftp.fao.org/docrep/fao/008/j5803e/j5803e00.pdf>2010 (verified 30 November 2010).
- FARAGE, P. K., ARDO, J., OLSSON, L., RIENZI, E. A., BALL, A. S. & PRETTY, J. N. (2007). The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modelling approach. *Soil and Tillage Research* **94**, 457–472.
- GARCIA, A. G. Y., HOOGENBOOM, G., GUERRA, L. C., PAZ, J. O. & FRAISSE, C. W. (2006). Analysis of the interannual variation of peanut yield in Georgia using a dynamic crop simulation model. *Transactions of the ASABE* **49**, 2005–15.
- GHOSH, P. K., MANNA, M. C., DAYAL, D. & WANJARI, R. H. (2006). Carbon sequestration potential and sustainable yield index for groundnut- and fallow-based cropping systems. *Journal of Agricultural Science, Cambridge* **144**, 249–259.
- GIJSMAN, A. J., HOOGENBOOM, G., PARTON, W. J. & KERRIDGE, P. C. (2002). Modifying DSSAT crop models for low input agricultural systems using a soil organic matter residue module form CENTURY. *Agronomy Journal* **94**, 462–474.
- GIJSMAN, A. J., THORNTON, P. K. & HOOGENBOOM, G. (2007). Using the WISE database to parameterize soil inputs for crop simulation models. *Computers and Electronics in Agriculture* **56**, 85–100.
- HAMMER, G. L., WOODRUFF, D. R. & ROBINSON, J. B. (1987). Effects of climatic variability and possible climatic change on reliability of wheat cropping: a modeling approach. *Agricultural and Forest Meteorology* **41**, 123–142.
- HERENCIA, J. F., RUIZ, J. C., MELERO, S., GARCIA GALAVIS, P. A. & MAQUEDA, C. (2008). A short-term comparison of organic v. conventional agriculture in a silty loam soil using two organic amendments. *Journal of Agricultural Science, Cambridge* **146**, 677–687.
- HIEN, E., GANDRY, F. & OLIVER, R. (2006). Carbon sequestration in a Savannah soil in southwestern Burkina as affected by cropping and cultural practices. *Arid Land Research and Management* **20**, 133–146.

- HOOGENBOOM, G., JONES, J. W., WILKENS, P. W., BATCHELOR, B. D., BOWEN, W. T., HUNT, L. A., PICKERING, N. B., SINGH, U., GODWIN, D. C., BAER, B., BOOTE, K. J., RITCHIE, J. T. & WHITE, J. W. (1994). Crop models. In *DSSAT v3, Decision Support System for Agrotechnology Transfer* Vol. 2. (Eds G. Y. Tsuji, G. Uehara & S. Balas), pp. 95–244. Honolulu, HI: University of Hawaii.
- HOOGENBOOM, G., JONES, J. W., WILKENS, P. W., PORTER, C. H., BATCHELOR, W. D., HUNT, L. A., BOOTE, K. J., SINGH, U., URYASEV, O., BOWEN, W. T., GUSMAN, A. J., DU TOIT, A., WHITE, J. W. & TSUJI, G. Y. (2004). *Decision Support System for Agrotechnology Transfer Version 4.0* (CD-ROM). Honolulu, HI: University of Hawaii.
- HUNT, L. A. & BOOTE, K. J. (1998). Data for model operation, calibration and evaluation. In *Understanding Options for Agricultural Production* (Eds G. Y. Tsuji, G. Hoogenboom & P. K. Thornton), pp. 9–39. Dordrecht, The Netherlands: Kluwer Academic Publishers.
- HUNT, L. A., PARARAJASINGHAM, S., JONES, J. W., HOOGENBOOM, G., IMAMURA, D. T. & OGOSHI, R. M. (1993). GENCALC: Software to facilitate the use of crop models for analyzing field experiments. *Agronomy Journal* **85**, 1090–1094.
- ILCA (1979). *Livestock Production in the Subhumid Zone of West Africa: A Regional Review*. ILCA Systems Study 2. Addis Ababa, Ethiopia: ILCA. Available online at: <http://www.fao.org/Wairdocs/ILRI/x5539E/x5539e03.htm-reliefandsoils> (verified 30 November 2010).
- JONES, J. W., GRAHAM, W. D., WALLACH, D., BOSTICK, W. M. & KOO, J. (2004). Estimating soil carbon levels using an ensemble Kalman filter. *Transactions of the ASAE* **47**, 331–339.
- JONES, J. W., HOOGENBOOM, G., PORTER, C. H., BOOTE, K. J., BATCHELOR, W. D., HUNT, L. A., WILKENS, P. W., SINGH, U., GUSMAN, A. J. & RITCHIE, J. T. (2003). DSSAT cropping system model. *European Journal of Agronomy* **18**, 235–265.
- KELLY, R. H., PARTON, W. J., CROCKER, G. J., GRACE, P. R., KLIR, J., KORSCHENS, M., POULTON, P. R. & RICHTER, D. D. (1997). Simulating trends in soil organic carbon in long-term experiments using the Century model. *Geoderma* **81**, 75–90.
- KOO, J., BOSTICK, W. M., JONES, J. W., GUSMAN, A. J. & NAAB, J. B. (2003). *Estimating Soil Carbon in Agricultural Systems using Ensemble Kalman Filter and DSSAT-CENTURY*. ASAE paper no. 33041. St. Joseph, MI: ASAE.
- LAL, R. (2000). Land use and cropping system effects on restoring soil carbon pool of degraded Alfisols in western Nigeria. In *Global Climate Change and Tropical Ecosystems* (Eds R. Lal, J. M. Kimble & B. A. Stewart), pp. 157–165. Boca Raton, FL: Lewis Publishers.
- LAL, R. (2007). Carbon management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change* **12**, 303–322.
- LAL, R., FOLLETT, R. F., STEWART, B. A. & KIMBLE, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science* **172**, 943–956.
- LEITE, L. F. C., DORAISWAMY, P. C., CAUSARANO, H. J., GOLLANY, H. T., MILAK, S. & MENDONÇA, E. S. (2009). Modeling organic carbon dynamics under no-tillage and plowed systems in tropical soils of Brazil using CQESTR. *Soil and Tillage Research* **102**, 118–125.
- MANDO, A., OUATTARA, B., SOMADO, A. E., WOPEREIS, M. C. S., STROOSNIJDER, L. & BREMAN, H. (2005). Long-term effects of fallow, tillage and manure application on soil organic matter and nitrogen fractions and on sorghum yield under Sudano-Sahelian conditions. *Soil Use and Management* **21**, 25–31.
- MCCARTHY, J. J., CANZIANI, J. F., LEARY, N. A., DOKKEN, D. J. & WHITE, K. S. (2001). *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press.
- MEINKE, H. & HAMMER, G. L. (1995). Climatic risk to peanut production: a simulation study for Northern Australia. *Australian Journal of Experimental Agriculture* **35**, 777–780.
- MOONEY, H. A. & KOCH, G. W. (1994). Impact of rising CO₂ concentrations on the terrestrial biosphere. *Ambio* **23**, 74–76.
- MTAMBANENGWE, F. & MAPFUMO, P. (2005). Organic matter management as an underlying cause for soil fertility gradients on smallholder farms in Zimbabwe. *Nutrient Cycling in Agroecosystems* **73**, 227–243.
- MUCHOW, R. C., HAMMER, G. L. & CARBERRY, P. S. (1991). Optimizing crop and cultivar selection in response to climatic risk. In *Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics* (Eds R. C. Muchow & J. A. Bellamy), pp. 235–262. Wallingford, UK: CAB International.
- NIJBROEK, R., HOOGENBOOM, G. & JONES, J. W. (2003). Optimizing irrigation management for a spatially variable soybean field. *Agricultural Systems* **76**, 353–377.
- NZIGUHEBA, N., MERCKX, R. & PALM, C. A. (2005). Carbon and nitrogen dynamics in a phosphorus-deficient soil amended with organic residues and fertilizers in western Kenya. *Biology and Fertility of Soils* **41**, 240–248.
- OADES, J. M. & WATERS, A. G. (1991). Aggregate hierarchy in soils. *Australian Journal of Soil Research* **29**, 815–828.
- OGLE, S. M., BREIDT, F. J., EASTER, M., WILLIAMS, S. & PAUSTIAN, K. (2007). An empirically based approach for estimating uncertainty associated with modelling carbon sequestration in soils. *Ecological Modelling* **205**, 453–463.
- OUATTARA, B., OUATTARA, K., SERPANTIE, G., MANDO, A., SÉDOGO, M. P. & BATIONO, A. (2006). Intensity cultivation induced effects on soil organic carbon dynamic in the western cotton area of Burkina Faso. *Nutrient Cycling in Agroecosystems* **76**, 331–339.
- OUÉDRAOGO, E., MANDO, A. & STROOSNIJDER, L. (2006). Effects of tillage, organic resources and nitrogen fertiliser on soil carbon dynamics and crop nitrogen uptake in semi-arid West Africa. *Soil and Tillage Research* **91**, 56–67.
- PARTON, W. J., SCURLOCK, J. M. O., OJIMA, D. S., GILMANOV, T. G., SCHOLES, R. J., SCHIMEL, D. S., KIRCHNER, T., MENAUT, J. C., SEASTEDT, T., GARCIA MOYA, E., KAMNARUT, A. & KINYAMARIO, J. L. (1993). Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochemical Cycles* **7**, 785–809.
- PICHT, J., SÉDOGO, M. P., POULAIN, J. F. & ARRIVETS, J. (1981). Fertility evolution in a tropical ferruginous soil under the effect of organic manure and inorganic fertilizer applications. *Agronomie Tropicale* **36**, 122–133.

- PORTER, C. H., JONES, J. W., ADIKU, S., GIJSMAN, A. J., GARGIULO, O. & NAAB, J. B. (2010). Modeling organic carbon and carbon-mediated soil processes in DSSAT V4.5. *Operational Research* **10**, 274–278.
- RAWLS, W. J. (1983). Estimating soil bulk-density from particle-size analysis and organic-matter content. *Soil Science* **135**, 123–125.
- REEVES, D. W. (1997). The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research* **43**, 131–167.
- DE RIDDER, N., BREMAN, H., VAN KEULEN, H. & STOMP, T. J. (2004). Revisiting a 'cure against land hunger': soil fertility management and farming systems dynamics in the West African Sahel. *Agricultural Systems* **80**, 109–131.
- RUSSELL, J. S. (1981). Geographic variation in seasonal rainfall in Australia: An analysis of the 80-year period 1895–1974. *Journal of the Australian Institute of Agricultural Science* **47**, 59–66.
- SCHLECHT, E., BUERKERT, A., TIELKES, E. & BATIONO, A. (2007). A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. In *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities* (Eds A. Bationo, B. Waswa, J. Kihara & J. Kimetu), pp. 1–28. Dordrecht, The Netherlands: Springer.
- SCHLESINGER, W. H. (1991). *Biogeochemistry: an Analysis of Global Change*. San Diego, CA: Academic Press.
- SOIL SURVEY STAFF (1999). *Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agriculture Handbook No. 436. Washington, DC: USDA Natural Resources Conservation Service.
- THORNTON, P. K., HOOGENBOOM, G., WILKENS, P. W. & BOWEN, W. T. (1995). A computer program to analyze multiple-season crop model outputs. *Agronomy Journal* **87**, 131–136.
- THORNTON, P. K., WILKENS, P. W., HOOGENBOOM, G. & JONES, J. W. (1994). Sequence analysis. In *DSSAT v3, Decision Support System for Agrotechnology Transfer* Vol. 3 (Eds G. Y. Tsuji, G. Uehara & S. Balas), pp. 67–136. Honolulu, HI: University of Hawaii.
- TIESSEN, H., CUEVAS, E. & CHACON, P. (1994). The role of soil organic matter in sustaining soil fertility. *Nature* **371**, 783–785.
- TIESSEN, H., FELLER, C., SAMPAIO, E. V. S. B. & GARIN, P. (1998). Carbon sequestration and turnover in semi-arid savannas and dry forest. *Climatic Change* **40**, 105–117.
- TSUJI, G. Y., JONES, J. W., HOOGENBOOM, G., HUNT, L. A. & THORNTON, P. K. (1994). Introduction. In *DSSAT v3, Decision Support System for Agrotechnology Transfer* Vol. 1 (Eds G. Y. Tsuji, G. Uehara & S. Balas), pp. 1–20. Honolulu, HI: University of Hawaii.
- TUCKER, C. J., FUNG, I. Y., KEELING, C. D. & GAMMON, R. H. (1986). Relationships between atmospheric CO₂ variations and a satellite derived vegetation index. *Nature* **319**, 195–199.
- VÄGEN, T. G., LAL, R. & SINGH, B. R. (2005). Soil carbon sequestration in sub-Saharan Africa: a review. *Land Degradation & Development* **16**, 53–71.
- VANLAUWE, B., AMAN, S., AIHOU, K., TOSSAH, B., ADEBIYI, V., SANGINGA, N., LYASSE, O., DIELS, J. & MERCKX, R. (1998). Alley cropping in the moist Savanna of West-Africa: III. Soil organic matter fractionation and soil productivity. *Agroforestry Systems* **42**, 245–264.
- WALKLEY, A. & BLACK, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38.
- WILLSON, T. C., PAUL, E. A. & HARWOOD, R. R. (2001). Biologically active soil organic matter fractions in sustainable cropping systems. *Applied Soil Ecology* **16**, 63–76.
- ZHANG, H., XU, M. & ZHANG, F. (2009). Long-term effects of manure application on grain yield under different cropping systems and ecological conditions in China. *Journal of Agricultural Science, Cambridge* **147**, 31–42.
- ZINGORE, S., MANYAME, C., NYAMUGAFATA, P. & GILLER, K. E. (2005). Long-term changes in organic matter of woodland soils cleared for arable cropping in Zimbabwe. *European Journal of Soil Science* **56**, 727–736.
- ZOUGMORE, R. B. (2003). *Integrated water and nutrient management for sorghum production in semi-arid Burkina Faso*. PhD thesis, Wageningen University. Available online at: <http://edepot.wur.nl/121487> (verified 30 November 2010).