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Modeling soil carbon sequestration in agricultural lands of Mali

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Abstract

Agriculture in sub-Saharan Africa is a low-input low-output system primarily for subsistence. Some of these areas are becoming less able to feed the people because of land degradation and erosion. The aim of this study is to characterize the potential for increasing levels of soil carbon for improving soil quality and carbon sequestration. A combination of high- and low-resolution imagery was used to develop a land use classification for an area of 64 km^2 near Omarobougou, Mali. Field sizes were generally small (10–50 ha), and the primary cultivation systems are conventional tillage and ridge tillage, where tillage is performed by a combination of hand tools and animal-drawn plows. Based on land use classification, climate variables, soil texture, in situ soil carbon concentrations, and crop growth characteristics, the EPIC-Century model was used to project the amounts of soil carbon sequestered for the region. Under the usual management practices in Mali, mean crop yield reported (1985–2000) for maize is 1.53 T ha^{-1}, cotton is 1.2 T ha^{-1}, millet is 0.95 T ha^{-1}, and for sorghum is 0.95 T ha^{-1}. Year-to-year variations can be attributed to primarily rainfall, the amount of plant available water, and the amount of fertilizer applied. Under continuous conventional cultivation, with minimal fertilization and no residue management, the soil top layer was continuously lost due to erosion, losing between 1.1 and 1.7 Mg C ha^{-1} over 25 years. The model projections suggest that soil erosion is controlled and that soil carbon sequestration is enhanced with a ridge tillage system, because of increased water infiltration. The combination of modeling with the land use classification was used to calculate that about 54 kg C ha^{-1} $year^{-1}$ may be sequestered for the study area with ridge tillage, increased application of fertilizers, and residue management. This is about one-third the proposed rate used in large-scale estimates of carbon sequestration potential in West Africa, because of the mixture of land use practices.

Keywords: Crop yields; Soil erosion; Land use classification; EPIC-Century model; Ridge tillage

1. Introduction

In the drought-prone Sudan-Sahelian zone of West Africa, agricultural operations are based on relatively low-input, low-output systems, which maintain production at subsistence levels. It is becoming more difficult to sustain the required food supply for the region because of land degradation from soil erosion and nutrient loss (Valentin et al., 2004; Igue et al., 2004; Wezel and Rath, 2002). The resulting low soil fertility, combined with the variable rainfall and low water holding capacity, limits the area's production of maize, sorghum and millet (Roose and Barthes, 2001). The primary soil-related constraints to production are water deficit, phosphorus (P) deficiency, and nitrogen (N) deficiency (M. Doumbia, personal communication).

The challenge of reversing the declining trend in agricultural productivity and conserving the environment for present and future generations in West Africa begins with the adaptation of proper management of natural and agricultural resources. Increasing the soil fertility and main-

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taining it at an optimum level is one of the key factors for sustainable agriculture. Soil fertility is especially affected by soil organic matter, which depends on biomass input to compensate rapid mineralization, leaching, and erosion (Roose and Barthes, 2001; Nandwa, 2001; M. Doumbia, personal communication). Soil organic matter (SOM) increases soil aggregation, resistance to rainfall impact, rate of infiltration, and soil flora and fauna (Roose and Barthes, 2001).

Studies have suggested that rapid decline of SOM levels is associated with continuous cultivation of crops in West Africa (Bationo et al., 1995; Bationo and Buerkert, 2001; Bationo et al., 2004). However, such declines may be site-specific and dependent on management practices such as the choice of the cropping system, soil tillage, and the application of mineral and organic soil amendments. In areas of the world where agriculture practices are primarily mechanized, such as in the US, conservation and no-till management practices are being adapted for increasing SOM and reducing erosion (Roose and Barthes, 2001; Six et al., 2002). In Mali, the option for minimum tillage may not be practical as cultivation is by primarily a combination of hand tools and animal-drawn plows. Furthermore, improved residue management for soil carbon buildup competes with other domestic needs such as cooking fuel and cattle feed. Carbon (C) losses by erosion from cropped land can be 4–20 times higher than on natural sites (Roose and Barthes, 2001). In Cameroon, a sharp decline in SOM was observed in the top layer (0–10 cm depth) of the conventional tillage due to accelerated mineralization (Roose and Barthes, 2001).

The average annual rainfall is about 600–1200 mm and crop yields are even more limited by low rainfall infiltration rates resulting in high surface runoff that causes extensive surface soil erosion and loss of needed water for crop growth. The seasonal rainfall that occurs primarily during July and August can be adequate to sustain crop growth, if infiltration is increased and the surface runoff is minimized.

Kablan et al. (2004) initiated a field study in agricultural sites in Mali to determine the effect of the ''aménagements en courbes de niveau'' practices (ridge tillage along contour lines, literally, ''installation in contour lines'') on soil moisture storage, and its potential impact on crop yield and soil carbon change. Ridge tillage, which is positioned across the slope, helps curtail water loss through reducing runoff and increasing infiltration rates. Points of same elevation are connected to form permanent major ridges called 'ados'. The technique begins with a survey of the field by the technician and farmer discussing water flow across the field and problems associated with runoff and erosion. A water management plan is jointly developed by the technician and farmer. For a given farm, one or several of the permanent ridges across the field are first constructed. Between the permanent ridges, row crops are planted on annually drawn ridges contoured according to the permanent ridges. Preliminary results indicate that early in the growing season, ridge tillage promotes a rapid downward movement of the wetting front and preserves more water in the topsoil right after a rainfall event (Brannan et al., 2004). Improved biomass production provides increased crop residue and thus increased carbon input to the soil.

The current research presented is part of an integrated ''Carbon from Communities'' study funded by NASA for an assessment of potential soil carbon sequestration in agricultural and pastoral systems located in the southeastern region of Mali. The objective was to estimate the potential for carbon sequestration and the interaction with yields for different management practices in the region. An important milestone in obtaining this objective was the development of an accurate land cover and land use map for the study site near Omarobougou to quantify the variation and spatial extent of the different land use practices in the study area. The EPIC-Century biogeochemical model was then used to simulate crop yields and the potential for soil carbon sequestration (Izaurralde et al., 2001a,b). The model simulates current and potential soil and crop management scenarios to optimize crop yield and soil carbon sequestration for conditions in Mali. An important characteristic of the model is the realistic simulation of the ridge tillage system and other cultural practices that are being evaluated by other investigators in this project.

2. Materials and methods

2.1. Site description

Mali is a tropical country located in the sub-Saharan region of West Africa. The country covers four climatic zones based on annual precipitation and topography. The area that was of interest in this study is defined as the Sudanian zone where the rainfall ranges between 650 and 1200 mm annually. The Omarobougou study site is located near the Commune of Koningué, with Sougoumba being the nearest village. This study site was selected because it was the site of demonstration plots to introduce ridge tillage practices to local farmers. The Omarobougou study site was approximately 64 km^2 in area, geographically located from a lower left corner of 12.136° N 5.182° W to upper right corner of 12.218° N 5.100° W. The landscape in general is rolling with agricultural fields predominantly in the relatively flat areas in the northern part of the study area, whereas in the southern part, there is rough terrain, which is covered with rocky material and shrubs. There are eroded soils and gullies caused by intense rainfall. The other vegetation covering in the surrounding area is short grass, shrubs, and trees.

The primary cash and subsistence crop is maize, which is cultivated near the villages. Cotton is the other major cash crop. Millet and sorghum are cultivated if there is adequate rainfall early in the season.

2.2. Weather data

The rainy season lasts from May to October, with July and August being the wettest months. The nearest meteorological station for this region is Koutiala (5.4° W 12.38° N), about 50 km from Omarobougou, with the mean annual rainfall of about 750 mm. Daily maximum temperature, minimum temperature, and rainfall data for 1970–2003 were obtained from the World Meteorological Organization (WMO) (http://www.worldweather.org/). Daily estimates of relative humidity and wind speed were obtained using the Agricultural Meteorology Modeling System (AGRMET, Hoke et al., 1981).

Since we are evaluating the long-term impact of management practices on soil carbon sequestration, weather data beyond 2003 are necessary for the model simulations. A weather generator (WxGEN, Richardson and Nicks, 1990) was used to produce climatic data beyond 2003. The stochastic weather generator WXGEN used the WMO 33-year historic daily records, including means and distribution characteristics of temperature and precipitation, to generate the 30 years of daily weather data beyond 2003 for each location.

2.3. Soils

The soils at the Omarobougou study are highly weathered and are classified as luvisol within the FAO classification system. Soils samples were collected from 17 locations in the region and were characterized to provide a range in soil properties (Table 1). Soil organic carbon was measured by automated dry combustion (CNS 2000, LECO Corp., St. Joseph, MI). Soil pH was determined in a 1:1 water suspension. Sand, silt, and clay fractions were measured by sedimentation using the pipette method (Gee and Bauder, 1986).

Soils at the Omarobougou site are sandy (55–83%), typical of this region of the Sahel, ranging in clay from 3% to 14% (Table 1). The range of measured soil pH had values between 4.5 and 6.2 (Table 1). Measured soil organic C contents ranged from 0.23% to 0.64% (Table 1), but are probably higher in the depressions and lower landscape positions. It has been hypothesized that the high susceptibility to erosion may be due to a low infiltration rate and the intensity of rainfall over a short rainy season. Evidence of severe erosion is widespread, even on soils with slopes of 5% or less.

The importance of maintaining soil organic C is crucial with low clay contents present in soil within the region because of low nutrient holding capacity and limited water holding capacity characteristic of such sandy soils. Soil nutrient status is predictably very low with soil pH values often below the 5.5 which is indicative of occasionally severe toxicity of aluminum (Al). Along with low soil organic C contents, there is corresponding low content of soil organic N. In summary, generally degraded agricultural soils in the region have severe nutrient deficiencies compounded by low nutrient retention capacity and low water holding capacity.

Table 1
Average and range in soil properties within the Omarobougou study area based on samples collected from agricultural fields ($n = 17$)

Statistic	Soil pH	Sand (%)	Silt (%)	Clay (%)	Soil C (%)
Average	5.3	72	22	6	0.23
Max	6.2	83	40	14	0.64
Min	4.5	55	10	3	0.12

2.4. Land cover classification

Land use is an important parameter that has a significant influence on the rate of soil carbon sequestration at local and landscape scales. In this study, the land use for the study area was assessed using satellite imagery acquired from various sensors. The classification of crops planted during the 2003 crop season was assessed to understand the distribution of the major crops cultivated in the study area and the total hectares of each crop. This information was used to develop the potential for total soil carbon sequestration in the study area surrounding the village in Omarobougou. Landsat enhanced thematic mapper (ETM) imagery is traditionally used for developing land use and crop classification for agricultural areas. The average field size at Omarobougou is small (10–50 ha), and it was impossible to distinguish fields and crop classes with Landsat ETM imagery which has a 30 m spatial resolution. Cloud cover during the summer monsoon season was another major problem in developing land use and crop classifications. Therefore, remote sensing data for this study were obtained from Quickbird (Digital Globe, Inc.) and SPOT (SPOT Image). Two Quickbird images (dates of 15 June 2003 and 3 August 2003) and two SPOT HRV images (dates of 14 October 2003 and 30 October 2003) were acquired. The Quickbird images have a spatial resolution of 2.44 m and bands in the Blue, Green, Red, and Near-infrared (NIR). The SPOT images have a spatial resolution of 10 m with bands in the Green, Red, NIR and Short-wave Infrared (SWIR, 1580–1750 nm).

All images were corrected to top of the atmosphere reflectance based on the calibration coefficients supplied by the two companies. The Quickbird image was the reference image used to register the SPOT images. Ground control points were acquired during site visits and were used to further rectify the Quickbird base image. Four sets of images were created from the satellite images for classification. The first was a collection of all 16 bands, which had some problems because of radiometric correlations among the bands. The second image was the first three principal components of all 16 bands. The third image was based on the following bands: Quickbird (15 June 2003: Red and NIR); Quickbird (3 August 2003: Green, Red and NIR); SPOT (14 October 2003: Red, NIR and SWIR); and SPOT (30 October 2003: Red, NIR and SWIR) for a collection of 11 bands that had maximum variation for the target land classes. The fourth image was the first three principal components from the 11 selected bands. In general, the Red and NIR bands are the most useful for studying agricultural areas. The SWIR band is useful for vegetation moisture content when used in combination with the NIR bands (Hunt and Rock, 1989; Hunt, 1991; Ceccato et al., 2002). The green bands and blue bands were less effective in the classification of this study area. For each image, target spectra were collected from "Areas of Interest" (AOI) based on ground samples. Forty classes were created for each image. The spectra signatures were used in a standard minimum distance supervised classification (ERDAS, 1992).

The four resulting classifications were compared and if a majority agreed, the pixel was assigned that land use class. If none of the classifications agreed, the fourth classification was used. For 10% of the area, where classifications were evenly split between the four classifications (two in each land use class), a complex set of rules was used to determine the final class. Due to a limit in the amount of ground truth that was collected, the ground truth that was used to classify the image was used for the accuracy assessment. Overall accuracy is the sum of all correctly classified ground sites divided by the total number of ground sites. Producer's accuracy and user's accuracy are used for accuracy assessment of individual classes. Producer's accuracy is the probability that a reference sample (ground data collected for the study region) will be correctly mapped and measures the errors of omission (1 – producer's accuracy). In contrast, the user's accuracy indicates the probability that a sample from land cover map actually matches what it is from the reference data (ground data collected) and measures the error of commission (1 – user's accuracy).

2.5. Biogeochemical model

The biophysical characteristics of each of these simulation environments (i.e., climate, soils, topography, etc.) were used as variables in the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1990) originally developed by the US Department of Agriculture and the Texas A&M Blacklands Research Center. The original version of the model was designed primarily to assess the impacts of soil erosion on crop productivity (Williams et al., 1984). EPIC can be adapted to a range of crop rotations, soil management practices and environmental conditions, and is used to predict yields for major crops in the study areas such as pearl millet, grain sorghum, maize, and cotton. The current version of the model is called Environmental Policy Integrated Climate (Mitchell et al., 1998), reflecting the evolution of the tool to include estimation of a variety of environmental indicators. Example applications include estimations of soil erosion from water (Chung et al., 1999; Phillips et al., 1993) and wind (Potter et al., 1998), climate change impacts on crop yield (Stockle et al., 1992; Brown and Rosenberg, 1999) and soil erosion (Favis-Mortlock et al., 1991; Lee et al., 1996). Izaurralde et al. (1998, 2001a,b) used this model to study carbon storage in eroded soils.

EPIC is a field-scale model designed to simulate drainage areas of up to 100 ha that are characterized by homogeneous weather, soil, landscape, crop rotation, and management system parameters. The model operates on a daily time-step. Tillage effects on surface residue, soil bulk density, mixing of residue and nutrients in the soil plow layer, and water and wind erosion are some of the major components and their interactions accounted for in the model. Curve number (CN) is a simplified index used to determine how much rain becomes runoff and thus enters the land drainage network. Given the influences on infiltration and run off such as antecedent moisture conditions, slope, runoff path, soil physical conditions, impact of vegetation, and some rainfall intensity. The method to apply the curve numbers was published by the Soil Conservation Service (US Department of Agriculture, 1985). To select the appropriate CN the following factors are taken into consideration including cover type, hydrologic condition, hydrologic soil group, and impervious area.

The EPIC model predicts surface runoff, return flow, percolation, ET and lateral subsurface flow. Water erosion; wind erosion; nitrogen (N) and phosphorus (P) loss in runoff, nitrogen leaching; organic N and P transport by sediment; N and P mineralization, immobilization and uptake; denitrification; N fixation; pesticide fate and transport; soil temperature; crop growth and yield for over 80 crops; crop rotations; tillage, plant environment control (drainage, irrigation, fertilization, furrow diking, liming) and economic accounting. An important update to the model in version EPIC1015, is an improved carbon cycling routine (Izaurralde et al., 2001a,b) which is extracted from the Century model that was developed by Parton et al. (1994). The carbon (C) and nitrogen components are simulated with three pools: active, slow, and passive. The movement of organic matter from surface litter to deeper soil subsurface layers and the resulting changes in C and N are calculated. Losses of C and N by leaching or gaseous forms are also accounted for in EPIC1015. The sensitivity analyses of the EPIC105 was conducted using long-term field studies and reported by Izaurralde et al. (2001b) and Gassman et al. (2003).

The earlier version of the EPIC model (Williams et al., 1984) is a widely tested and adapted model originally built to quantify the effects of erosion on soil productivity. It has since evolved into a comprehensive agro-ecosystem model capable of describing the behavior of many crops grown in complex sequences and tillage operations (Williams, 1995). EPIC has subroutines to calculate wind and water erosion. Water erosion is caused by the energy in rainfall and runoff and is calculated using six different equations (Izaurralde et al., 2001a,b). Concepts and equations from the Century model as described by Parton et al. (1993, 1994) and Vitousek et al. (1994) were used to build a sub model in EPIC describing C and N transformations in soil and link these to the dynamic simulation of water erosion executed on a daily time step.

2.6. Model application

The EPIC1015 model requires initial values for the soil carbon pools, which were estimated from the total soil carbon (Table 1). However, a period of time is required during the simulations for the soil carbon pools to reach steady state. Thus, simulations were started in the year 1970 with conventional tillage and fertilizer management. Under conventional tillage and fertilizer management, fields were plowed with moldboard plow, followed by surface application of manure and fertilizer, sowing of seeds, harvest, and removing most crop residue. We assumed conventional management left 15% of residue on the ground after planting. Changes of simulated field management began in 2003 and continued for 25 years with five different scenarios: (1) conventional management with minimum fertilizer applications, (2) ridge management with minimum fertilizer applications, (3) conventional management with increased fertilizer applications, (4) ridge management with increased fertilizer applications, and (5) ridge management with increased fertilizer applications and residue management.

In ridge-tillage management, the seedbed was prepared by creating contour ridges and using furrow dikes to prevent water erosion. Dikes were 0.30 m high and 13 m apart; ridges were 0.30 m high and 0.75 m apart. Dikes and ridges are assumed to be rebuilt during the crop season or after any breakdowns of the dikes and ridges. Planting on ridge tops was assumed to remove 2–5 cm of soil and residue from the ridge by sweeping. Plants in the ridge till system have about 30 cm of extra topsoil above the standard convention tilled soil. Another difference in ridge vs. conventional till is that the curve numbers used in their simulations are slightly lower for ridge till system (82 vs. 88). The selection of the curve numbers are based on the EPIC model documentation on curve number application obtained from the National Engineering Handbook (US Department of Agriculture, 1972).

Table 2 summarizes the variation in nutrient inputs among the different managements and the conventional application rates for the first two scenarios, which were based on information obtained from local farmers and collaborators from the Institute d'Economie Rurale, Ministry of Agriculture. For the increased fertilizer simulations in the last three scenarios, the incremental application rates of fertilizer were based on the minimal requirement to prevent nutrient deficit conditions when the model was run continuously over several decades cultivating the same crop. One of the model outputs is the daily nutrient deficit condition and there is an automatic adjustment of the nitrogen and phosphorous application rates required to prevent nutrient deficit to occur. This exercise was conducted over conventional till simulations to keep the same level of yields throughout the simulation period.

Table 2
Fertilizer and manure rates obtained from the Mali Ministry of Agriculture

Management scenario	Crops	Manure (kg ha^{-1}) × 1000	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})
Conventional	Cotton	1	37	6
	Maize	1	22	6
	Millet	0	18	9
Ridge	Sorghum	0	10	5
	Cotton	1	37	6
	Maize	1	22	6
	Millet	0	18	9
Conventional + increased fertilizer	Sorghum	0	10	5
	Cotton	1	67	9
	Maize	1	37	9
	Millet	0	38	9
Ridge + increased fertilizer	Sorghum	0	34	10
	Cotton	1	67	9
	Maize	1	37	9
	Millet	0	38	9
Ridge + residue + increased fertilizer	Sorghum	0	34	10
	Cotton	1	67	9
	Maize	1	37	9
	Millet	0	38	9
	Sorghum	0	34	10

The regional crop yields for maize, sorghum, millet, and cotton were acquired from archive databases (TAMU, 2000; Diall, 2001). The EPIC1015 model parameters that affected crop yields were adjusted to produce the range of expected yields from the study region using the climatic database and reported management practices and crop yield statistics (Somé et al., 2003).

3. Results and discussion

3.1. Land use classification

Fig. 1 is the final classification for the Omarobougou study site representing an area of 64 km^2. The image was categorized into seven predominant classes of interest in this study namely, cotton, maize, sorghum, millet, grass, trees, shrubs, bare soil, and roads. Maize crop was about 17.5% of the total land area, the largest area for crops, followed by cotton and millet with 13.4% and 12.3%, respectively.

Table 3 shows that accuracy for individual land use classes were mixed and the overall accuracy of the land use classification was 70.3%. Millet, maize, and sorghum could not be separated on one image due to the similar growth forms, and could not be separated temporally because of differences in planting dates, and therefore were combined into one class. The producer accuracy of the combined millet, maize, and sorghum class was reasonable, but the user accuracy was low due to confusion with cotton. On the other hand, the user accuracy of the cotton class was reasonable whereas the producer accuracy of the cotton class

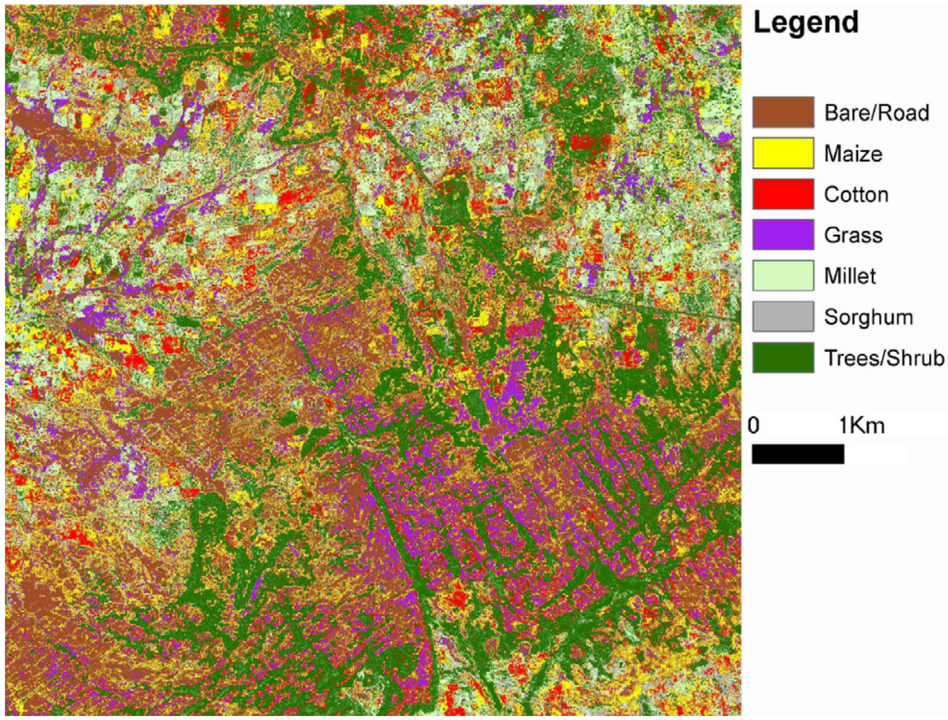

Fig. 1. Land cover classification for the Omarobougou study region.

was low due to confusion with the millet, maize, and sorghum class (Table 3). For Fig. 1 and in the simulation analysis, the millet, maize and sorghum classification area was partitioned into individual crops based of fractions and distribution of ground observations.

Trees, shrub and grass classes had low user accuracies (Table 3). One of the reasons that the user accuracy for trees is very low is because the ground data did not delineate every tree that was located within each field. Thus, trees within fields are considered misclassifications. Sparse crops can also be misclassified as grass causing problems with the user accuracy but not with the producer accuracy.

3.2. Annual water budgets resulting from management system

The annual precipitation for the Omarobougou study region averages 743 mm, which was reproduced in the simulations using the WxGEN weather generator. For any given year, the simulated monsoonal precipitation fell primarily over 2 months, with the beginning of the monsoonal season being early or delayed by up to 1 month, similar to the weather data. With the natural variability in beginning and ending dates, we calculated a single, mean year which resulted in 743 mm of precipitation which was distributed over a 4-month period, instead of the average 2-month period. The consequence of using a mean year was less daily rainfall and lower rainfall intensity, which reduced runoff and erosion. Therefore the WxGEN weather simulations provided more realistic conditions than a mean year to estimate erosion in the Omarobougou study region. The WxGEN weather generator did simulate the year-to-year variation of the beginning and ending of the rainfall period. The planting dates were set based on the onset of the rainfall period.

Table 3
Accuracy assessment for the study region in Omarobougu using Quickbird imagery

	Ground data	Image class (no. of pixels)							User accuracy (%)
		Road	Cotton	Millet, maize, and sorghum	Shrub	Bare	Trees	Grass	
	Road	214	0	11	0	0	0	0	95.11
	Cotton	0	5281	703	62	26	16	3	86.7
	Millet, maize, and sorghum	0	3556	8708	184	108	73	0	68.95
	Shrub	0	153	51	212	7	2	0	49.88
	Bare	0	185	75	35	646	0	0	68.65
	Trees	0	465	377	24	11	160	0	15.4
	Grass	0	89	249	1	59	0	210	34.54
Producer accuracy (%)		99.07	54.28	85.59	40.93	75.38	63.75	98.59	
Overall accuracy (%)									70.28

The EPIC1015 model simulations indicated that maize fields would have the highest runoff under conventional tillage (Table 4). Simulations for ridge tillage reduced runoff for each crop type by 52–60 mm annually compared to conventional tillage. Larger plant sizes with increased fertilizer also reduced simulated runoff, but the reduction was only 16–17 mm annually. Increased fertilizer with ridge tillage, with or without residue management, did not greatly affect simulated runoff beyond the reductions made by ridge tillage alone (Table 4). Besides water lost by runoff, some of the precipitation is intercepted and evaporated, and the remainder of the precipitation infiltrates the soil. Simulated infiltration continues until the soil reaches the field water holding capacity, then any additional water inputs to the soil percolates below the root zone defined by crop type, where it is not available for transpiration. Simulations with ridge tillage show that percolation increased compared to conventional tillage (Table 4). However, the extra infiltrated water keeps the soil at the field water holding capacity for a longer period of time.

Simulations of evaporation from the soil and transpiration from the growing crop (together termed evapotranspiration or ET) draw down the amount of water stored in the soil. Simulated evapotranspiration is higher with ridge tillage compared to conventional tillage (Table 4) because increased infiltration puts more water in the root zone. Based on the daily solar energy, daily totals of evapotranspiration are about 5 mm, so the increased water available from ridge tillage could supply the crops with 6–8 days of transpiration at the maximum rates. Transpiration is increased and evaporation is decreased with crop size and cover resulting from increased fertilization, but the sum of evaporation and transpiration is more or less determined by the tillage and crop system (Table 4). Residue management with retention of surface residues reduces simulated evaporation, so, the simulated annual total of evapotranspiration is reduced somewhat (Table 4).

3.3. Crop yields as a result of management system

Simulated yields for the four crops are highly variable and depend on the annual precipitation. The simulated yields of conventional tillage for all four crops were in the range of the yields from Sikasso, which is the closest to the study area in Omarobougou. The long-term yields (1992–2000) for conventional tillage for Cotton, Maize, Millet and Sorghum reported by the Ministry of Agriculture for the Sikasso area were 1.21 T ha^{-1}, 1.53 T ha^{-1}, 0.96 T ha^{-1}, and 0.95 T ha^{-1}, respectively. The ridge till management system does not seem to have a large effect on simulated crop yields of cotton, but had large effects on maize, millet, and sorghum (Table 5). Increased fertilizer increases simulated yields more than ridge tillage and there is a synergistic interaction between increased fertilizers with ridge tillage to increase yields in maize, millet, and sorghum. Addition of residue management to ridge tillage and increased fertilizer increases the yields slightly for maize, millet, and sorghum (Table 5). Water use efficiency (crop yield per annual precipitation) increases similar to the increase in yields for all four crops.

Table 4
Twenty-five year averages of the annual water budget for the study region in Omarobougou

Management scenario	Crops	ET (mm)	Percolation below root zone (mm)	Runoff (mm)
Conventional	Cotton	549	25	168
	Maize	491	36	213
	Millet	537	28	174
	Sorghum	511	33	196
Ridge	Cotton	580	48	112
	Maize	522	55	161
	Millet	575	44	120
	Sorghum	555	49	136
Conventional + increased fertilizer	Cotton	552	37	151
	Maize	492	51	196
	Millet	539	42	158
	Sorghum	514	47	178
Ridge + increased fertilizer	Cotton	580	48	112
	Maize	521	64	154
	Millet	575	51	114
	Sorghum	553	57	129
Ridge + residue + increased fertilizer	Cotton	573	57	110
	Maize	512	74	152
	Millet	563	61	113
	Sorghum	547	66	126

The annual precipitation average was 743 mm.

Table 5
Model simulated mean and variance of crop yield for the 25-year period for the various crops and management scenarios

Management scenario	Crops	Mean yield (T ha^{-1})	Standard deviation
Conventional	Cotton	1.35	0.41
	Maize	1.33	0.21
	Millet	1.10	0.24
	Sorghum	0.79	0.12
Ridge	Cotton	1.79	0.65
	Maize	1.78	0.21
	Millet	1.42	0.33
	Sorghum	1.11	0.21
Conventional + increased fertilizer	Cotton	1.53	0.55
	Maize	1.85	0.33
	Millet	1.60	0.45
	Sorghum	1.64	0.21
Ridge + increased fertilizer	Cotton	1.79	0.65
	Maize	2.32	0.29
	Millet	1.97	0.52
	Sorghum	2.11	0.21
Ridge + residue + increased fertilizer	Cotton	1.86	0.68
	Maize	2.63	0.32
	Millet	2.12	0.55
	Sorghum	2.26	0.23

3.4. Soil carbon sequestration as a result of management system

Ridge tillage with increased fertilizer and residue management significantly increased the simulated amount of carbon sequestered in the slow and passive soil organic matter pools for all four crops (Fig. 3). Ridge tillage with increased fertilizer also increased the amount of carbon sequestration for maize, millet, and sorghum, but not as much as including residue management (Fig. 3). Increasing crop biomass with either ridge tillage (improved water relations) or conventional tillage with increased fertilizer without ridge tillage allowed about equal inputs to the soil and thus about equal amounts of soil carbon sequestered for maize, sorghum, and millet as model output did not show significant differences in carbon mineralization between these two management systems (Fig. 3). Soils with conventional tillage, without additional fertilizer, are expected to continue to lose soil organic carbon for all four crops and consequent reduction in biomass yields (Fig. 3).

Over 1 mm of soil per year was projected to be lost under conventional tillage (Table 6), which is close to the averages presented in den Biggelaar et al. (2004a,b). Ridge tillage reduces simulated soil erosion by 55–70% (Table 6). Adding crop residue and extra fertilizer to ridge tillage further reduced erosion by about 40–60% compared to ridge tillage alone (Table 6). However, displaced soil carbon due to soil erosion was not reduced as much with added crop residue (Table 6), because of the higher average SOC content (Fig. 3). According to Lal (2003), some of the displaced carbon due to soil erosion settles on other parts of the landscape, some settles as sediment, and about 20% is lost to the atmosphere. Therefore, reducing the amount of erosion is considered saving SOC compared to the baseline of conventional tillage. Table 6 shows that there is a modest amount of SOC saved by the prevention of erosion with the adoption of ridge tillage.

Whereas the SOC content has year-to-year variation (Fig. 3) due to differences in annual precipitation (Fig. 2) over the 25 years of the simulations, conventional tillage losses averaged about 20 kg C ha^{-1} $year^{-1}$ (Table 6). These losses can be considered the baseline for carbon sequestration credits, which may help fund any additional fertilizer and alternative fuel sources. Simply preventing further loss of SOC would thus be a 20 kg C ha^{-1} $year^{-1}$ sequestered compared to a business as usual scenario (conventional tillage with low fertilizer application). With increased fertilizer and conventional tillage, only sorghum exceeds the carbon sequestration level of 20 kg C ha^{-1} $year^{-1}$ (Table 6). Ridge tillage exceeds this level with carbon sequestration from 27 to 34 kg C ha^{-1} $year^{-1}$ (Table 6). Ridge tillage with increased fertilizer and residue management would lead to sequestration of about 4–7 times this base level, since carbon is being added to the soil (Table 6). The highest values in Table 6 for carbon sequestration over the baseline fall in the middle of the ranges assumed by Lal (2002) in his calculation for the potential sequestration of carbon on cropland in tropical soils.

Table 6
Summary of carbon losses and gains over 25 years for the study region in Omarobougou[a]

Management scenario	Crops	Erosion loss thickness (mm)[b]	SOC displaced by erosion (kg ha^{-1}) × 1000	SOC saved (kg ha^{-1})[c]	SOC change (kg ha^{-1}) × 1000	Carbon credit (kg ha^{-1} $year^{-1}$)[d]
Conventional	Cotton	24.5	1.10	0	−0.49	
	Maize	25.3	1.15	0	−0.71	
	Millet	36.5	1.69	0	−0.47	
	Sorghum	20.7	1.10	0	−0.59	
Ridge	Cotton	10.7	0.66	88	0.02	24
	Maize	11.5	0.76	79	−0.12	27
	Millet	12.6	0.89	159	0.18	32
	Sorghum	5.8	0.59	101	0.21	36
Conventional + increased fertilizer	Cotton	22.8	1.04	13	−0.36	6
	Maize	23.4	1.11	8	−0.27	18
	Millet	32.2	1.54	29	0.14	26
	Sorghum	18.9	1.07	5	0.12	29
Ridge + increased fertilizer	Cotton	10.1	0.64	91	0.09	27
	Maize	10.4	0.77	76	0.54	53
	Millet	10.8	0.88	161	1.21	74
	Sorghum	4.8	0.59	102	1.28	79
Ridge + residue + increased fertilizer	Cotton	6.5	0.70	79	1.52	84
	Maize	6.0	0.76	78	1.99	111
	Millet	6.3	0.89	158	2.73	134
	Sorghum	2.0	0.56	107	2.95	146

[a] Total study area is 6400 ha.
[b] Assuming a soil bulk density of 1.5 Mg m^{-3}.
[c] Twenty percentage of displaced SOC lost to atmosphere (Lal, 2002, 2003), amount saved compared to erosion losses with conventional tillage.
[d] SOC gain or loss compared to conventional tillage as baseline and carbon saved from erosion losses compared to conventional tillage.

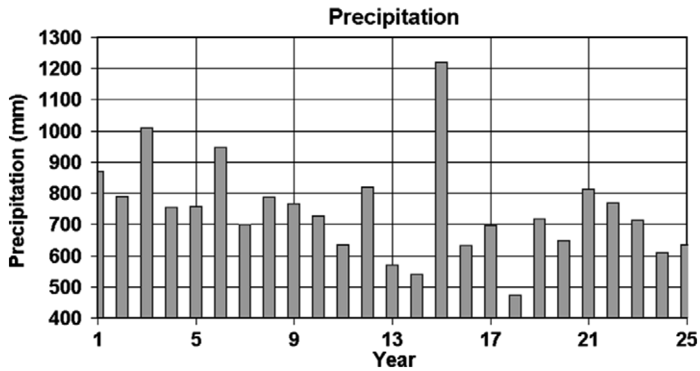

Fig. 2. Precipitation for the study region for 2003 (year 1) and simulated data for the next 24-year period based on the WGEN model.

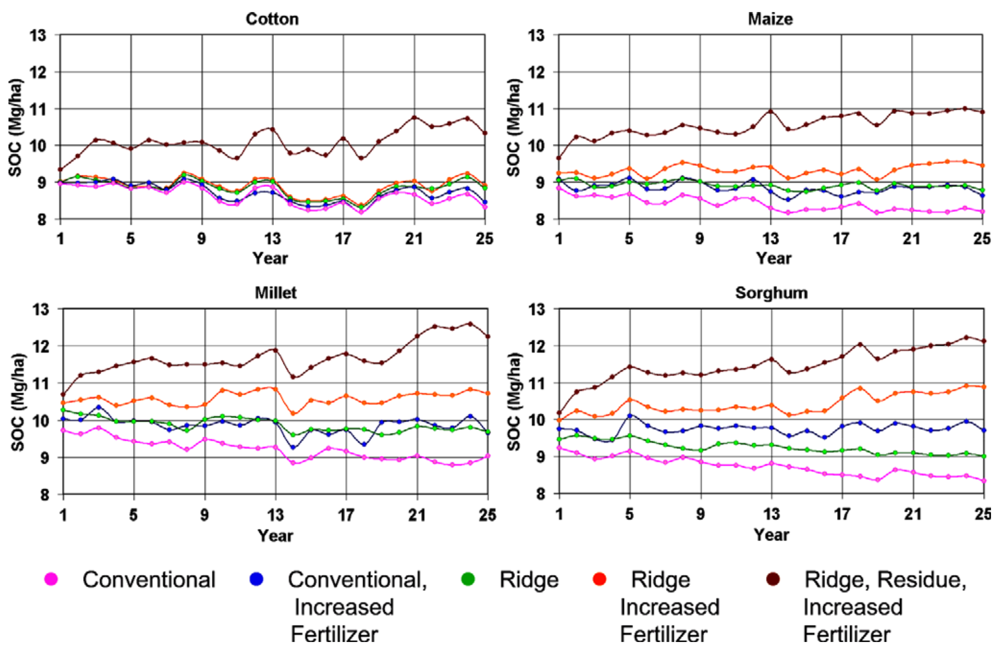

Fig. 3. Simulation results of soil organic carbon for the various management scenarios over a 25-year period.

However, not all of the Omarobougou study area is used for crops. Averages on the basis of area covered by each of the crops for ridge tillage with increased fertilizer and the residue management shows that the potential for simulated carbon sequestration is 54 kg C ha^{-1} $year^{-1}$ over baseline. This is about one-half the rate of carbon sequestration assumed by Lal (2002). At larger scales, the entire Omarobougou study area would be classified as crops by remote sensing, so regional budgets assuming the higher rate of carbon sequestration would be in error.

3.5. Cost effectiveness of carbon sequestration

Based on the current (2005) market in Mali, the prices are $US 0.222 kg^{-1} for cotton, $US 0.111 kg^{-1} for maize, and $US 0.083 kg^{-1} for millet and sorghum. From the expected yields for conventional tillage, gross revenue ranges from about $66 ha^{-1} for sorghum to $300 ha^{-1} for cotton (Table 7). Conventional tillage with increased fertilizer increases gross revenue for maize, millet, and sorghum, compared to ridge tillage. However, the combination of ridge tillage with increased fertilizer increases gross revenue (Table 7) above any conventional tillage scenario. Assuming $10 Mg^{-1} as the price that might be paid for sequestering carbon, even the most optimistic scenario of ridge tillage, increased fertilizer, and residue management only gains from $0.84 to $1.46 ha^{-1} $year^{-1}$. The increased cost of additional fertilizer was more than recouped through increased yield. Scenario 5, with the addition of residue management to increased fertilizer and ridge tillage produced the highest net revenue for all four crops, primarily because of increased yields, not carbon payments (Table 7). The economic incentives from a western perspective may not be very much, however the Mali farmers needs every bit of income to keep farming their lands and the potential for increase in yields with fertilizer application in a ridge till system is encouraging.

Table 7
Average annual economic estimates for the different management scenarios

Management scenario	Crops	Gross revenue ($ ha^{-1})[a]	Carbon revenue ($ ha^{-1})[b]	Fertilizer costs ($ ha^{-1})[c]	Net revenue ($ ha^{-1})[d]
Conventional	Cotton	299.97	0	13.14	286.83
	Maize	147.76	0	8.56	139.21
	Millet	91.66	0	8.25	83.41
	Sorghum	65.83	0	4.58	61.25
Ridge	Cotton	397.74	0.24	13.14	384.84
	Maize	197.76	0.27	8.56	189.47
	Millet	118.33	0.32	8.25	110.40
	Sorghum	92.50	0.36	4.58	88.27
Conventional + increased fertilizer	Cotton	339.97	0.06	23.22	316.80
	Maize	205.54	0.18	14.06	191.66
	Millet	133.33	0.26	14.36	119.22
	Sorghum	136.66	0.29	13.44	123.51
Ridge + increased fertilizer	Cotton	397.74	0.27	23.22	374.79
	Maize	257.75	0.53	14.06	244.23
	Millet	164.16	0.74	14.36	150.54
	Sorghum	175.83	0.79	13.44	163.17
Ridge + residue + increased fertilizer	Cotton	413.29	0.84	23.22	390.90
	Maize	292.19	1.11	14.06	279.25
	Millet	176.66	1.34	14.36	163.64
	Sorghum	188.33	1.46	13.44	176.34

[a] Prices are \$0.222 kg^{-1} for cotton, \$0.111 kg^{-1} for maize, and \$0.083 kg^{-1} for millet and sorghum.
[b] Price for carbon sequestration is \$10.00 Mg^{-1}.
[c] Cost for N (urea) and P (diammonium phosphate) is \$0.305 kg^{-1}.
[d] Does not include cost for labor.

Missing from this preliminary analysis is the extra labor costs for ridge tillage compared to conventional tillage, labor costs for fertilizer application, residue management, and costs to replace residue for fuel and fodder. Because two of the three missing costs are for scenario 5, the net revenue for ridge tillage, increased fertilizer and residue management would be lower than indicated in Table 7. However, ridge tillage and increased fertilizer should increase net agricultural revenue, with or without carbon markets.

4. Conclusions

Poor water management associated with intense rain events causes excessive soil loss from the field as well as reduced water availability for crop production. There are several fronts that have been addressed by the "Carbon from Communities" team. This simulation analysis indicates that implementation of ridge tillage management, for better water management, combined with increased nutrient inputs, substantially could increase crop yields and economic returns for farmers. Additionally, soil quality could be improved as indicated by increased soil organic carbon. However, the economic returns associated with increased soil carbon via carbon credits (\$10 Mg^{-1} C) were small relative to expense of fertilizers and income from increased yields. Most remote sensing studies in West Africa have used Landsat imagery that cannot resolve the small field size and often cluster crop land classifications with non-cropped land. In this study, we used a high-resolution land use classification that showed only a portion of the total study area was in cropland. This means that the simulated improved soil condition associated with the crop management scenarios would not be spread equally to the entire study area, thus, reducing the amount of potential carbon sequestration on a regional basis.

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