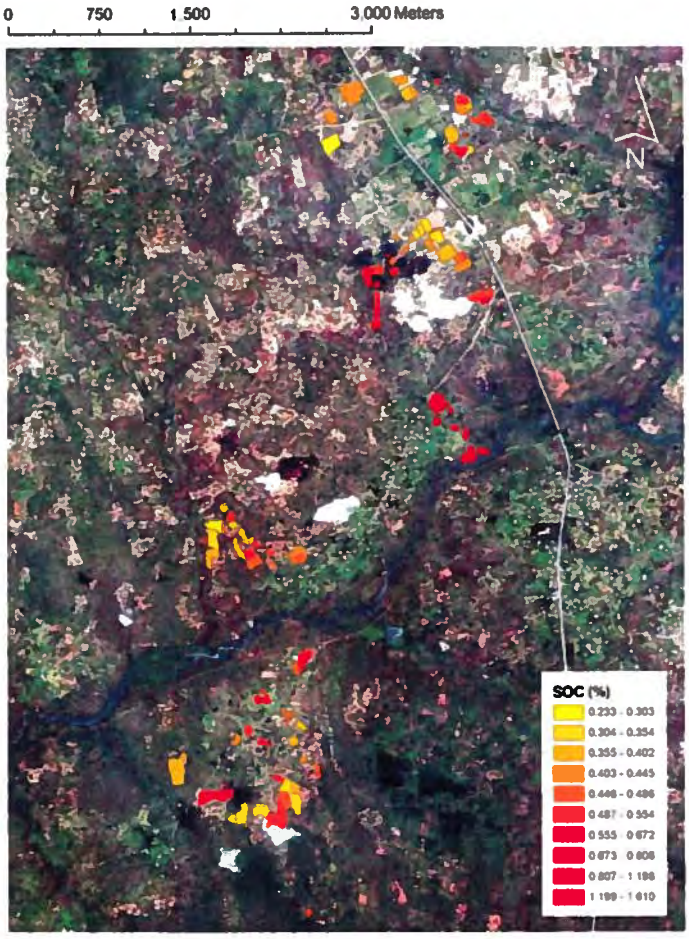
PN-ADS-400

CARBON ENHANCING MANAGEMENT SYSTEMS (CEMS)

Estimation of Soil Carbon Sequestration Potential in Small-holder Farming Systems in Northern Ghana



UF UNIVERSITY of FLORIDA IFAS

CSIR

Soil Management C R S P

USAID FROM THE AMERICAN PEOPLE

AUGUST 2008

CARBON ENHANCING MANAGEMENT SYSTEMS (CEMS)

Estimation of Soil Carbon Sequestration Potential in Small-holder Farming Systems in Northern Ghana

Jesse B. Naab
Savannah Agricultural Research Institute, Wa Research Station, Ghana and
Department of Agricultural and Biological Engineering, University of Florida, USA

Jawoo Koo
Department of Agricultural and Biological Engineering, University of Florida, and
IFPRI, Washington, DC, USA

Pierre C.S. Traore
ICRISAT, Bamako, Mali and
Department of Agricultural and Biological Engineering, University of Florida, USA

Samuel G.K. Adiku
Department of Soil Science, University of Ghana, Legon, Accra, Ghana and
Department of Agricultural and Biological Engineering, University of Florida, USA

James W. Jones
Department of Agricultural and Biological Engineering, University of Florida, USA

Kenneth J. Boote
Department of Agronomy, University of Florida, USA

AUGUST 2008

Cover photo: Farmer fields from 4 villages sampled in 2004 and 2006.

Photo credit: All photographs courtesy of Jawoo Koo.

Designer: Robin Snyder

Acknowledgment

This study was made possible by the generous support of the American people through the United States Agency for International Development (USAID). The contents are the responsibility of the Soil Management CRSP (Grant No. LAG-G-00-97-00002) to the University of Florida and do not necessarily reflect the views of the USAID or the United States Government.

OVERVIEW

It is now generally accepted that soils constitute the largest and safest terrestrial store of carbon. Hence, soil carbon (SOC) accumulation is an effective way of reducing the rising atmospheric carbon dioxide, one of the main greenhouse gases contributing to global climate change. A major challenge is, however, the reliable and accurate quantification of how much SOC storage occurs over a given time period. The challenge arises for several reasons:

(i) SOC is highly variable in time and actual detectable net increases only occur over long periods of time,
(ii) SOC has high spatial variability, requiring measurements over relatively large spatial scales for reliable estimates, and
(iii) Not all land management or farming practices lead to increases in SOC accretion.

The above challenges must be met for reliable estimation of SOC changes under different land management systems, which would require time consuming and costly sampling and analysis. To arrive at frequent estimates that would meet the terms of carbon credit verification, additional methods are required to supplement field measurements. Recently, SOC models have emerged that have the capability of estimating SOC and its changes over time under different land management systems. A popular SOC model is CENTURY. By linking CENTURY with the DSSAT suite of crop models, a new tool has emerged that is capable of investigating SOC dynamics under different cropping practices. This tool has the advantage of simultaneously simulating both the growth and yields of crops and SOC. Thus the combination of limited SOC measurement, augmented with SOC modeling provides an opportunity for investigating the long term SOC changes in a time and cost-effective manner.

The purpose of this bulletin, the second in a series, is to estimate potential soil C sequestration for different management options in small holder farming communities in Northern Ghana using a method that combines direct measurement with simulation modeling.

METHODS

Site Description and Farming Practices

The study site was located south of Wa in the Upper West Region of Ghana (Latitude 10.02 N and Longitude -2.38 W), which is characterized by a mean annual temperature of 32°C and a mean annual rainfall of 1200 mm. The rainy season extends from May thru October. For the rest of the year, the weather is dry and warm. Vegetation is a guinea savanna woodland. Soils are predominantly sandy and classified as alfisols or ferric luvisols.

Farm surveys were conducted in 2004 and 2006 in 4 villages, namely Nakor, Kparisaga, Kumfabiala, and Bamahu, within an area of about 18 km^2 to collect information on field size and boundaries, cropping history during the last 5 years, and crop residue and soil fertility management practices. Subsistence farming was the dominant practice and crops grown in the area are cereals (maize, sorghum, millet, and rice), legumes such as groundnut, cowpea, soybean, and bambara nut, and root and tuber crops (yam, cassava, and sweet potato). Cropping sequence varied greatly but the most popular was alternating cereal crops with fallow (cereal-fallow), which was practiced in 57 fields (43%). Cereal crops were continuously cultivated for about four

Figure 1: Residues left in the field after harvest

years, before fields were left fallow for about four years. In some cases (11 fields, or 8%) legumes were cultivated between cereals and fallow (cereal-legume-fallow) with typically about two years of cereal followed by two years of legumes alternated with four years of fallow. Out of 132 fields, 96 fields (73%) were intercropped in at least one year during the five-year period.

Crop residues of maize, sorghum, and groundnut are usually left on the field after harvest and slowly decompose **(Figure 1)**. Part of the residues is typically removed by grazing livestock and termites or harvested by the household for feeding livestock or fuel wood. At the beginning of the rainy season, farmers gather the remaining crop residues **(Figure 2)** and collect them in several spots in the field **(Figure 3)**. Roots are typically dug up and added to the aboveground residues **(Figure 4)** before burning. Use of mineral fertilizers is not common in the area but maize may be fertilized. Out of the 132 fields in this study, only one maize field was fertilized with 1 bag (50 kg) N-P-K compound fertilizer.

Soil sampling and analysis

A total of 132 farmer fields from 4 villages were sampled in 2004 and 2006 (cover photo). In each field, a composite soil sample consisting of 5 to 6 sub-samples were taken from the 0- to 20-cm depth. Soil texture and organic carbon were determined using the hydrometer and Walkley-Black methods respectively at the Savanna Agricultural Research Institute Laboratory in Wa. Additionally, a soil profile pit was dug at Nakor and the soil was sampled at different depths to measure changes in properties with depth. These data provided important data on the SOC over space and time and also for parameterizing the DSSAT-CENTURY model.

Figure 2: Residues after cutting

Figure 3. Collected residues

Simulation Model and Inputs

The DSSAT-CENTURY model used in this study has three main components - the crop, soil and management modules. The crop module simulates development, growth and yield while the soil module simulates water and nutrient balance and SOC dynamics. The management module implements crop choice, crop rotation sequences, tillage and fertilizer application. The model requires input of daily weather (solar radiation, rainfall minimum and maximum temperature) and soil data. The soil data were derived from properties determined on the soil profile at Nakor village. Twenty years of daily minimum and maximum temperature, solar radiation and rainfall data for input to the DSSAT-CENTURY model were estimated using the DSSAT software based on 8 years of daily weather measurements from Wa, Ghana. Growth of two cereals (maize, millet), and one legume (groundnut) were selected for study. Genetic coefficients for the millet were calibrated by Folliard (2004), those for groundnut by Naab et al. (2004), and those for maize were derived from field measurements at Wa (Koo, 2007).

The relevant question is: how will the SOC change from year to year over a 19-year period under different farming practices. To answer this, we identified 5 land management or farming practices (Table 1).

Using the measured SOC data in 2006 as the starting point, crop yields and SOC were simulated for each of the farming practices for 20 years. From this, the annual carbon sequestration rate of any practice was calculated relative to FP as:

Change in [SOC] relative to FP (kg ha^{-1} yr^{-1}) =

$$((TRT_{in} - TRT_{i0}) - (FP_n - FP_0)) / n$$

Where:

n = year
i = management system
TRT_{in} = amount of SOC for management system i in year n, kg SOC ha^{-1}
FP_n = amount of SOC for FP in year n, kg SOC ha^{-1}

Thus, the relative change in SOC concentration rate for each farming practice represented the net potential soil carbon benefit relative to the FP management system over time.

RESULTS

SOC Changes in Farmer Fields

The cover photo shows the range of soil organic carbon measured in the 132 farmer fields in the study area. Using pooled data from the 132 farmer fields, it was observed that in 2004 SOC concentration ranged from 0.23 to 1.61 g kg^{-1} while in 2006 SOC ranged from 0.31 to 1.33 g kg^{-1} (Table 2). On a mass basis, the median SOC values were equal to 14.7 Mg ha^{-1} in 2004 and 14.3 Mg ha^{-1} in 2006 based on a bulk density of 1.63 g cm^{-3} for the top 20 cm soil depth.

Farm practices clearly affected SOC despite the short time interval from 2004 to 2006. For example, farms that produced legumes and tubers had slightly less SOC in 2006 than in 2004. Farms that returned more biomass to the soil, mainly those producing cereals, had slightly more SOC in 2006 than in 2004. As one might expect, it appears that to increase SOC practices must include a large proportion of biomass to the soil.

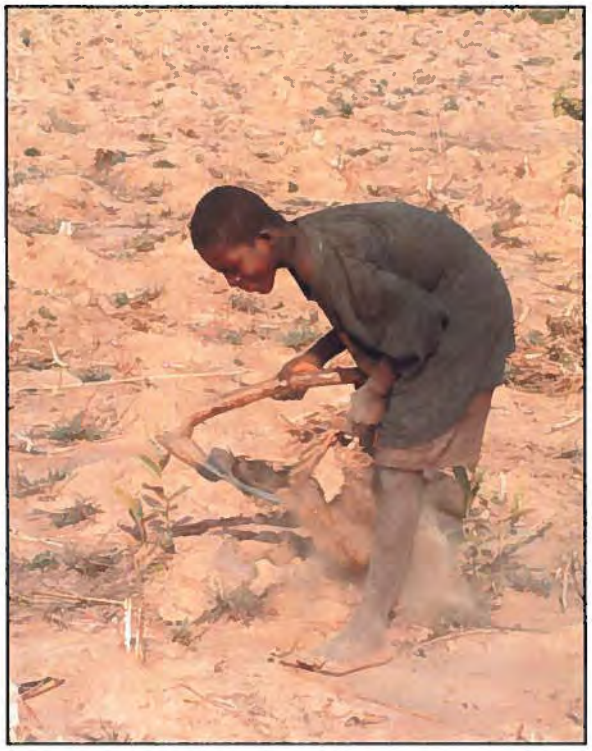


Figure 4: Removal of roots

Table 1. Production practices used for different simulated crop management systems.

Management system (Abbreviation)	Tillage	Fertilization	Residue removal	
			Cereals	Legumes
Farmer practice (FP)	Hand-hoe to 20 cm depth	No fertilization	100%	75%
No-till (NTL)	No-till	No fertilization	25%	25%
Fertilization (FRT)	Hand-hoe to 20 cm depth	Maize: 40 kg N ha^{-1} yr^{-1} Millet: 20 kg N ha^{-1} yr^{-1} Peanut: No fertilization	100%	75%
Leaving residues (RSD)	Hand-hoe to 20 cm depth	No fertilization	25%	25%
Recommended management practice (RMP)†	No-till	Maize: 40 kg N ha^{-1} yr^{-1} Millet: 20 kg N ha^{-1} yr^{-1} Peanut: No fertilization	25%	25%

† Recommended by Lal (2004)

Table 2. ***Descriptive statistics of the SOC measurements in 132 farmer fields in Wa, Ghana, during 2004 and 2006.***

Year	No. of samples	Soil organic carbon (g kg^{-1} soil)				
		Minimum	Maximum	Median	Average	Standard deviation
2004	132	0.23	1.61	0.45	0.53	0.26
2006	132	0.31	1.33	0.44	0.50	0.20

POTENTIAL PRODUCTION

Biomass production

Continuous maize mono-cropping showed the most distinctive responses to fertilization, compared to other crops (Table 3). The hand hoeing with fertilizer application and the recommended management practices showed higher biomass productivities (7.7 Mg ha^{-1}) than the practices (farmer practice, no-till, and residue retention) without fertilization. Relative to the farmer practice, the fertilized management systems significantly enhanced biomass productivity by more than 90% on average (Table 3). In contrast, no-till and residue retention management systems without fertilization showed only slightly higher productivity than the farmer practice. This result implied nutrient-depleted soil fertility and nutrient-limited productivity in the simulated cropping system. On average, annual aboveground vegetative biomass was slightly less than 8 Mg ha^{-1} for the hand hoeing with fertilizer application and recommended management practices and about 4 Mg ha^{-1} for the no-till, residue retention, and farmer practices without fertilizer.

Continuous millet mono-cropping also showed differences in biomass production for each management system (Table 3). Hand hoeing with fertilizer application produced significantly more than the farmer practice, no-till, and residue retention without fertilizer management systems. Productivity was increased further with the recommended management practice, which produced more than twice as much biomass as the farmer practice (Table 3). Unlike maize, the no-till and residue retention without fertilizer management systems showed significantly higher biomass productivity than the baseline farmer practice (Table 3).

In the legume-based system, continuous groundnut mono-cropping did not show any noticeable differences in aboveground biomass production (Table 3). Presumably, soil nutrients (especially N) were not limiting because of biological fixation.

Grain yield

Continuous maize with fertilizer application but residues removed and recommended practices produced average grain yield of 3.7 Mg ha^{-1} each while the farmer, no-till and residue retention practices without fertilizer management systems produced average grain yields of 1.3, 1.3 and 1.4 Mg ha^{-1} respectively (Table 3). Relative to the farmer practice, the fertilized management systems increased grain yield on average by 178%. In contrast, the no-till and residue retention without fertilization management systems

Table 3. ***Simulated vegetative biomass production and grain yields for continuous mono-cropping systems under the different management systems.***

Cropping system	Management system	Mean biomass (Mg ha^{-1})	Mean grain yield (Mg ha^{-1})
Continuous maize	FP	4.0 ± 0.3	1.32 ± 0.15
	NTL	4.1 ± 0.3	1.33 ± 0.13
	FRT	7.7 ± 0.3	3.67 ± 0.19
	RSD	4.4 ± 0.2	1.44 ± 0.12
	RMP	7.7 ± 0.3	3.69 ± 0.20
Continuous millet	FP	3.6 ± 0.4	0.64 ± 0.07
	NTL	4.4 ± 0.4	0.77 ± 0.06
	FRT	6.3 ± 0.4	1.03 ± 0.07
	RSD	5.0 ± 0.3	0.84 ± 0.06
	RMP	7.5 ± 0.3	1.19 ± 0.07
Continuous groundnut	FP	4.7 ± 0.3	1.37 ± 0.15
	NTL	4.7 ± 0.3	1.38 ± 0.15
	FRT	4.7 ± 0.3	1.37 ± 0.15
	RSD	4.7 ± 0.3	1.39 ± 0.15
	RMP	4.7 ± 0.3	1.38 ± 0.15

FP = Farmer practice involving hand hoeing, no fertilization and residue removal
NTL = No-till with no fertilizer application
FRT = Hand hoeing with fertilizer application to cereals
RSD = Leaving crop residues on the field with no fertilizer application
RMP = Recommended management practice involving no-till, fertilization and crop residue retention

showed only slight increases of 0.5% and 8.9%, respectively, over the farmer practice. For continuous millet the farmer practice produced typical low grain yield of 644 kg ha^{-1}. Continuous millet under no-till without fertilizer or with residue retention but no fertilizer slightly increased grain yield compared with the farmer practice, but were generally less than 1 Mg ha^{-1}. Continuous millet production by hand hoeing with fertilizer application or with the recommended practices produced significantly greater average grain yields (> 1.0 Mg ha^{-1}) compared with farmer practice.

As with the biomass production, groundnut pod yield was similar for all management systems (Table 3). On average all management practices produced 1.3 Mg ha^{-1}, which is more than the national average groundnut yield of 0.8 Mg ha^{-1}.

Table 4. ***Simulated mean total soil organic carbon (SOC) to 20 cm depth after 19 years for continuous mono-cropping systems under different management systems in a representative farmer fields in Wa, Ghana.***

Cropping system	Management system	Mean SOC ($Mg\ ha^{-1}$)	Increase over FP (%)
Continuous maize	FP	11.2 ± 0.2	-
	NTL	12.5 ± 0.1	12.2
	FRT	11.5 ± 0.2	3.2
	RSD	11.8 ± 0.1	5.6
	RMP	13.2 ± 0.1	18.1
Continuous millet	FP	10.6 ± 0.2	-
	NTL	12.9 ± 0.1	21.2
	FRT	10.7 ± 0.2	0.8
	RSD	12.0 ± 0.1	13.3
	RMP	14.1 ± 0.2	32.5
Continuous groundnut	FP	11.5 ± 0.2	-
	NTL	12.9 ± 0.1	12.0
	FRT	11.5 ± 0.2	0.0
	RSD	12.2 ± 0.1	6.0
	RMP	12.9 ± 0.1	12.0

FP = Farmer practice involving hand hoeing, no fertilization and residue removal
NTL = No-till with no fertilizer application
FRT = Hand hoeing with fertilizer application to cereals
RSD = Leaving crop residues on the field with no fertilizer application
RMP = Recommended management practice involving no-till, fertilization and crop residue retention

Soil carbon sequestration

Soil organic carbon for each cropping system also responded significantly to management systems (Table 4). The recommended management practices sequestered the most carbon of all cropping systems, followed by the no-till system. For all crops, the hand hoeing with fertilizer application showed the least soil carbon sequestration potential. Although hand hoeing with fertilizer application increased biomass productivity in all crops (Table 3), the enhanced crop biomass production did not result in soil carbon sequestration

Table 5. ***Simulated soil carbon content and change relative to the farmer practice after 19 years, aggregated over 132 farmer fields in Wa, Ghana.***

Management system	SOC content (Mg ha^{-1})	SOC difference with FP (kg ha^{-1})	Change in SOC relative to FP (kg ha^{-1} yr^{-1})
FP	12.7	-	-
NTL	15.2	2,516	132
FRT	13.2	488	23
RSD	14.1	1,350	71
RMP	16.1	3,344	173

FP = Farmer practice involving hand hoeing, no fertilization and residue removal
NTL = No-till with no fertilizer application
FRT = Hand hoeing with fertilizer application to cereals
RSD = Leaving crop residues on the field with no fertilizer application
RMP = Recommended management practice involving no-till, fertilization and crop residue retention

because most crop residues were removed. In contrast, no-till and leaving residues on the field increased soil organic carbon in all crops, which indicates that even without fertilization, improved residue management can effectively increase soil carbon sequestration. On average, continuous millet mono-cropping and with recommended management practices annually sequestered 30% more soil carbon than the farmer practice and had the highest soil carbon sequestration potential of 14.1 Mg ha^{-1} (Table 4).

Aggregate soil carbon sequestration

As an aggregated regional estimate of soil carbon sequestration potential, results from all 132 fields were averaged by management system (Table 5). The aggregated results showed soil carbon contents of 16.1 Mg ha^{-1} for the recommended management practices and 15.2 Mg ha^{-1} no-till management system, both of which increased SOC over the 19-year simulation period. Residue retention and fertilizer application management systems showed less potential, although SOC levels were greater than that of the farmer practice (Table 5). The fertilizer application management system showed the least improvement over farmer practice among management systems.

On average, all simulated management systems had greater SOC than the farmer practice (Table 5). The change in SOC relative to farmers practice over the 19 years of simulation was 173 kg SOC ha^{-1} yr^{-1} for the recommended management practices, which was significantly more than fertilizer application without residue retention (FRT) and residue retention without fertilizer application (RSD) systems. Without fertilizer applications, the no-till and residue retention systems had soil carbon sequestration rates of 132 kg SOC ha^{-1} yr^{-1} and 71 kg SOC ha^{-1} yr^{-1}, respectively. These values were significantly higher than the management system in which fertilizer was applied but residues removed, which had an

average soil carbon sequestration rate of about 23 kg SOC ha^{-1} yr^{-1}. The residue retention management system (sequestration rate of 71 kg SOC ha^{-1} yr^{-1}) was not as effective as the no-till or recommended management practices, but still showed a significantly higher soil carbon sequestration rate than the farmer practice and fertilizer application management systems. The fertilizer application management system sequestration rate of 23 kg SOC ha^{-1} yr^{-1} was significantly lower than that for the no-till, residue retention, and recommended management practices, although it was significantly higher than the farmer practice.

SUMMARY AND CONCLUSIONS

- Measurement of SOC from 132 farm fields in the Wa area of Ghana indicated generally low values ranging from 0.02 to 1.61% with an average value of 0.50%. Changes over a two year period (2004 to 2006) were only very slight even though cereal-based cropping practices appeared to support SOC enhancement more than legume and tuber-based cropping practices.
- Simulation results showed that SOC accumulation was enhanced with residue retention and fertilizer application to cereal crops, whereas the current farmer practice led to the decline of SOC over time.
- When recommended practices were adopted, the regionally aggregated soil carbon sequestration rate was estimated to be 173 kg SOC ha^{-1} yr^{-1}.
- Small doses of fertilizer applications showed significant aboveground biomass production in cereals, but they did not benefit soil carbon sequestration without changes in residue management and tillage practices.
- Solely relying on fertilizer without returning crop residues showed the least potential in sequestering soil carbon.
- Although average crop biomass production under no-till was less than the tilled practice, the soil carbon sequestration potential under no-till was significantly higher than the tilled system.
- Consequently when fertilization is not a feasible option, the most effective management practice to sequester soil carbon would be no-till farming.
- The overall results showed positive potential of adopting conservation tillage and/or residue management practices, but the adoption of these practices by the smallholder farmer would require some education and support to overcome any social and economic barriers. Some of these measures may include carbon credit payments, support for agro-chemicals and training. These and others were discussed in greater detail in our third technical bulletin.

REFERENCES

Folliard, A., Traore, P.C.S., Vaksmann, M., Kourssy, M. 2004. Modeling of sorghum response to photoperiod: a threshold-hyperbolic approach. Field Crops Research 89:59-70.

Koo, J. 2007. Estimating soil carbon sequestration in Ghana. Ph.D. Thesis, University of Florida, Gainesville, FL, USA, pp 200.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. Geoderma 123:1-22.

Naab, J.B., Singh, P., Boote, K.J., Jones, J.W., and Marfo, K.O. 2004. Using the CROPGRO-peanut model to quantify yield gaps of peanut in the Guinean Savanna Zone of Ghana. Agronomy Journal 96:1231-1242.

For further information, please contact:

J.B.Naab: jbnaab@africaonline.com.gh

or

Koo Jawoo: J.Koo@cgiar.org