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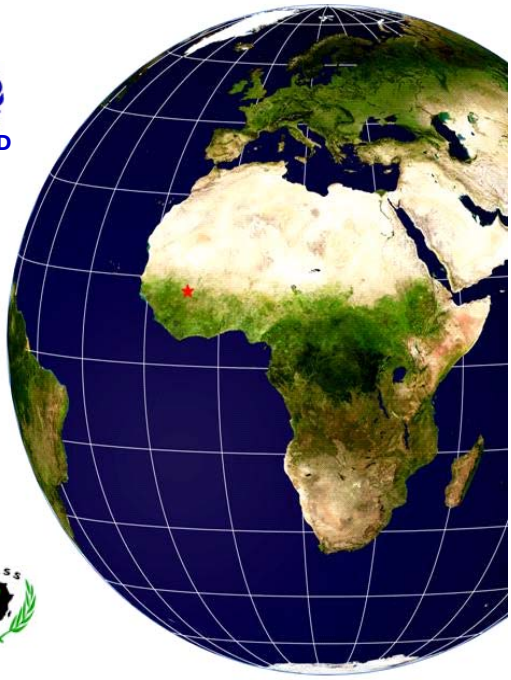

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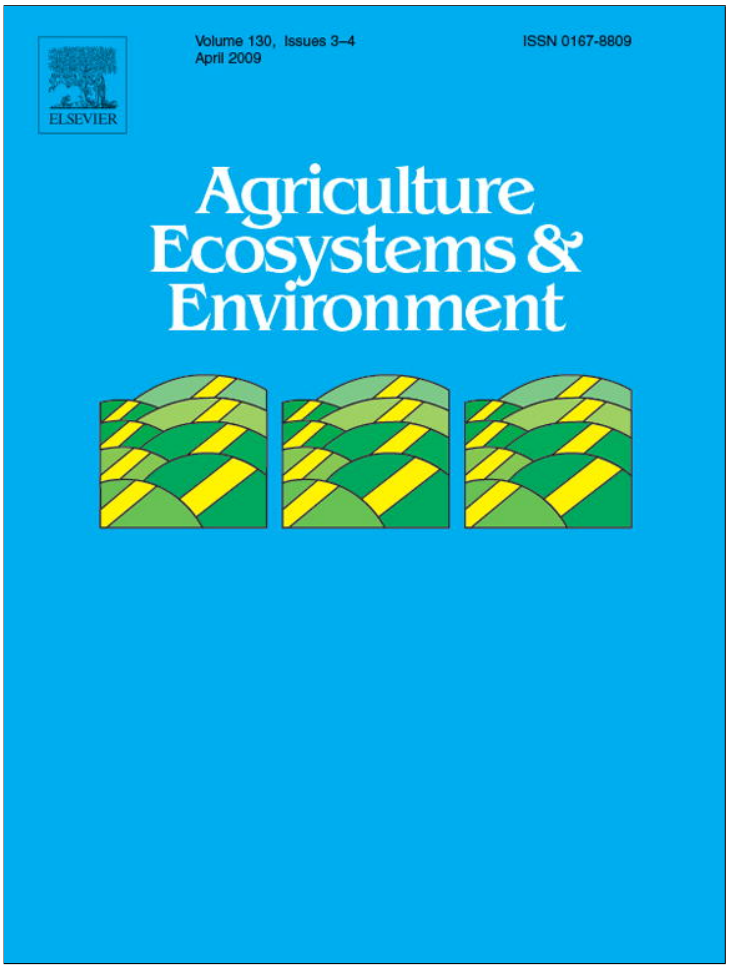

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Simulated dynamics of carbon stocks driven by changes in land use, management and climate in a tropical moist ecosystem of Ghana

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ABSTRACT

Sub-Saharan Africa is large and diverse with regions of food insecurity and high vulnerability to climate change. This project quantifies carbon stocks and fluxes in the humid forest zone of Ghana, as a part of an assessment in West Africa. The General Ensemble biogeochemical Modeling System (GEMS) was used to simulate the responses of natural and managed systems to projected scenarios of changes in climate, land use and cover, and nitrogen fertilization in the Assin district of Ghana. Model inputs included historical land use and cover data, historical climate records and projected climate changes, and national management inventories. Our results show that deforestation for crop production led to a loss of soil organic carbon (SOC) by 33% from 1900 to 2000. The results also show that the trend of carbon emissions from cropland in the 20th century will continue through the 21st century and will be increased under the projected warming and drying scenarios. Nitrogen (N) fertilization in agricultural systems could offset SOC loss by 6% with 30 kg N ha^{-1} $year^{-1}$ and by 11% with 60 kg N ha^{-1} $year^{-1}$. To increase N fertilizer input would be one of the vital adaptive measures to ensure food security and maintain agricultural sustainability through the 21st century.

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1. Introduction

Concerns about impacts of global warming on ecosystem performance are motivating scientists to determine the extent to which changes in land use and land cover (LULC) and land management have affected and continue to affect the global carbon (C) budget, nutrient cycling, and sustainability of ecosystems. Many studies have been conducted to assess how both LULC and recent climatic trends have impacted ecosystems of West Africa (Gonzalez, 2001; Nicholson, 2001; Liu et al., 2004a; Woomer et al., 2004; Tan et al., 2009). Increasing attention is being paid to sub-Saharan Africa because this area probably makes a greater contribution to the uncertainty of the C budgets at regional and global scales than any other regions (Houghton and Hackler, 2006).

Deforestation for crop production has been a dominant force leading to a substantial loss of ecosystem C stock in sub-Saharan Africa. It not only contributes to the global greenhouse effect but also jeopardizes ecosystem services. For example, deforestation-induced fragmentation can greatly increase the susceptibility of tropical ecosystems to fire in dry years (Laurance, 2004) and in turn provide a positive feedback to climate change by releasing C from soil and reducing evapotranspiration (Field et al., 2007). Meanwhile, the replacement of forests by annually harvested croplands largely reduces the C accumulation associated with forests in response to elevated CO_2 (Field et al., 2007). Therefore, deforestation-induced change in LULC requires critical consideration in model simulations for predicting the responses of ecosystems to climate change in the future. For this study, we selected the Assin district of Ghana, a tropical moist ecosystem, as the study area. Our hypothesis is that changes in LULC and management practices have been the primary forces leading to net C sources across the area during the 20th century, and the uncertainties of interannual climate and the application level of nitrogen (N) fertilizers will be major factors controlling ecosystem C dynamics in the future. The specific objectives of this study are to identify the dynamics of ecosystem C and soil organic carbon (SOC) stocks during the 20th century and to simulate the sensitivity of both natural and managed ecosystems to projected climate changes, deforestation, and nitrogen fertilization through the 21st century.

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2. Materials and methods

2.1. Study area

The Assin district is in the central part of southern Ghana and covers an area of 2416 km^2. The mean annual minimum and maximum temperatures for this area between 1971 and 2000 were 22.3 °C (±0.4) and 32.3 °C (±0.6), respectively. During the same period, the region mean annual precipitation was 1421 mm (±186) and about 86% of the total annual precipitation occurred between March and October. The natural vegetation community was thought the tropical moist forest. By 2000, closed forest (>60% cover), degraded forest (<60% cover, derived from natural closed forest due to cutting and other disturbances), and agriculture (with 10–20 trees ha^{-1}) were major LULC types and accounted for 20.3%, 34.1%, and 44.0%, respectively, in 2000 (Table 1). Between 1975 and 2000, a net area change in LULC amounted 15% of the total land area, primarily as conversions from both closed forest and degraded forest to cropping systems. During this time, closed forest decreased by 20.6% and degraded forest declined by 22.2%, whereas the area of cropland increased by 50.1%. Major crop species included maize (*Zea mays* L.), cassava (*Manihot esculenta*), and cocoyam (*Xanthosoma tannia*). Of the total planted area in 2000, these crops accounted for 45%, 40%, and 10%, respectively.

2.2. Modeling system and simulations

2.2.1. GEMS (General Ensemble biogeochemical Modeling System)

The modeling approach applied in Senegal by Liu et al. (2004a) was used in this study to help develop an understanding of the climate and management controls on the biogeochemical cycling in the more humid country of Ghana. We believed that the model structure and performance of GEMS with results validated in Senegal could provide a solid basis for application in Ghana.

GEMS (Liu et al., 2004b) was developed for a better integration of well-established ecosystem models with various spatial databases for simulating biogeochemical cycles over large areas (Liu et al., 2004a). The CENTURY model (Parton et al., 1987) was selected as the underlying ecosystem biogeochemical model in GEMS because it has solid modules for simulating C dynamics at the ecosystem level and has been widely applied to various ecosystems worldwide. GEMS has been successfully used to simulate C dynamics in vegetation and soil at various spatial scales. More detail about this model can be referred to Liu et al. (2004b).

Similar to the model application in Senegal by Liu et al. (2004a) modeling architecture in this study was designed for three scenarios: initial C status around 1900, impacts of human disturbances on C dynamics from 1900 to 2000, and C trends under a changing climate from 2000 to 2100. For initial C status around 1900, it was assumed that the ecosystem C flux and SOC stock in 1900 were in equilibrium under natural vegetation, even though human presence could be traced back prior to 1900. Estimates of ecosystem C flux and SOC stock in 1900 were obtained by running GEMS for 1500 years (so that the equilibrium of SOC stock was supposed to reach and the stabilized values of SOC stock in 1900 can be used as the baselines for simulations) under natural vegetation, coupled with the data of climatic variables (including mean monthly precipitation, mean monthly minimum and maximum temperatures) from 1971 to 2000 (climatic data are available only for this time period), and contemporary soil and drainage conditions. As defined by CENTURY SOM model (Parton et al., 1987), SOC stock consists of three pools: labile, slow and passive. According to Paustian et al. (1995), we used a retrospective SOC initialization algorithm to define the slow SOC pool based on the NPP (net primary productivity) for each land cover type and soil inventory data. The labile SOC pool was set at about 5% of the total SOC stock. The difference between the total SOC and both the slow and labile pools was then used to initialize the passive SOC pool.

2.2.2. Geospatial data for model simulations

The spatial simulation unit of GEMS is a JFD (joint frequency distribution) case. A JFD case (i.e. a grid) contains multiple, homogeneous, connected or isolated land pixels that represent a unique combination of values from the Geographic Information System (GIS) layers. The GIS layers for JFD generation in this study consisted of mean monthly precipitation, mean monthly minimum and maximum temperatures, historical LULC change dynamic data that were derived from 1975 to 2000 Landsat images provided by Ghana Environmental Protection Agency and Center for Remote Sensing and Geographical Information System (CERSGIS), soil inventory taken from the FAO soil database. A total of 36 JFD cases with a pixel size of 1 km by 1 km were resulted from the combination of these GIS layers in this study.

2.2.3. Management practice data

The information of management practices for this study was synthesized from sample site investigations across the study area and the literature. The dataset of management practices for model simulations consisted of crop composition, crop rotation, fallow, and harvesting options (or residue management). These kinds of information and their parameters used in GEMS are listed in Table 2. Besides crop residues retained in field, an average level of 2.0 Mg ha^{-1} $year^{-1}$ manure was considered for modeling. Both hand- and animal-driven plowing methods were applied for tillage. The frequency of fuelwood production from woodlands was assumed to be one time each year. GEMS automates the processes of downscaling those data for C budget simulations.

2.2.4. Ensemble simulations and uncertainty control

According to Liu et al. (2004b), GEMS generates site-level inputs with a Monte Carlo approach from regional datasets. Because any single simulation of a JFD case is a unique combination of the spatial units in common of all input GIS layers, the output of a

Table 1
Land use/land cover types and their changes in the Assin district from 1975 to 2000.

Land use and land cover type	1975		2000		Change by	
	km^2	%[a]	km^2	%[a]	km^2	%[a]
Closed forest (>60%)	618	25.6	491	20.3	−127	−5.3
Degraded forest	1061	43.9	825	34.1	−236	−9.8
Agriculture	709	29.3	1064	44.0	355	14.7
Water	8	0.3	8	0.3	0	0.0
Settlement	20	0.8	28	1.2	8	0.3
Sum	2416	100	2416	100		
Area changed					363	15.0

[a] Percentage of the total land area.

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Table 2
Parameters of management practices used in model simulations.

Period	Closed cultivated land			Open cultivated land			Widely open cultivated land		
	Maize	Cocoyam	Cassava	Maize	Cocoyam	Cassava	Maize	Cocoyam	Cassava
A. Percentage of each crop in all planted area (crop composition)									
1900–1986	25	60	15	19	24	23	10	11	10
1987–1990	40	45	15	20	23	22	9	10	8
1991–2000	45	40	15	20	22	20	10	8	9

	Maize	Cocoyam	Cassava
B. Probabilities of crop rotation			
Maize	0.20	7.00	0.10
Cocoyam	0.50	0.40	0.10
Cassava	0.40	0.35	0.25

Land use type	Years in fallow		Years in cropping	
	Minimum	Maximum	Minimum	Maximum
C. Fallow schedule				
Cultivated with 20 trees	4	5	1	5
Cultivated with 10 trees	5	6	1	4

Period	GH	G50	G
D. Fraction of harvested area associated with harvesting options			
1900–1930	0.5	0.3	0.2
1931–1960	0.3	0.5	0.2
1961–1990	0.0	0.2	0.8
1991–2000	0.0	0.0	1.0

Note: GH, harvesting all grain and stalk; G50, harvesting grain and 50% of stalk; G, harvesting grain only.

single simulation run of a JFD might be biased. Therefore, ensemble simulations of each JFD are executed to incorporate the variability of inputs. In general, the outputs of ensemble simulations become more stable when increasing the number of simulation runs (Liu et al., 2004b). We made 20 repeat runs for each JFD case in this study to insure stable outputs. Values of selected output variables were written to a set of output files after each model execution and then aggregated for the study area using SAS Macros programming. Meanwhile, the uncertainty of simulations was evaluated in terms of the coefficient of variation (CV) with all model outputs. More importantly, we used the field observation data of the ecosystem C and SOC stocks and the grain yields of major crops as references to verify the corresponding outputs, and repeatedly ran model simulations by adjusting parameters after each run until the outputs matched the field measurements as closely as possible. As illustrated in Fig. 1, the model simulations can catch about 92% variance of SOC stock estimation based on the comparison of simulated and measured results from 18 sampling sites within the study area for the year 2006 (because soil samples were collected in May of 2006). Therefore, the model outputs should represent the general patterns of C dynamics across the study area.

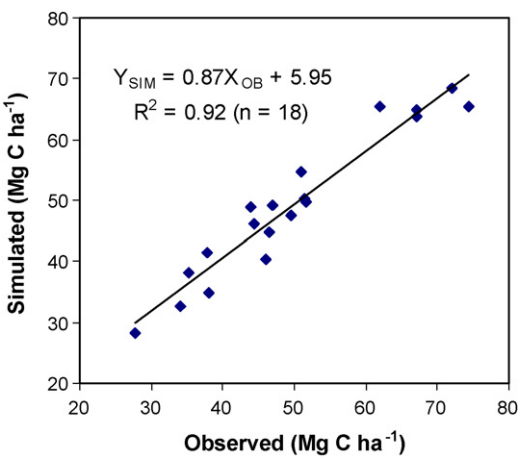

Fig. 1. Comparison of GEMS simulated and observed soil organic carbon stocks for the top 20 cm depth in 2006. The slope and intercept of the regression line are not significantly different from 1 and 0, respectively.

2.3. Simulation scenarios

2.3.1. Scenarios for the 20th century

We set the initial C status around 1900 by running the GEMS under the natural vegetation condition, and then ran GEMS for the 20th century using the input data as described above and management data (see Table 2). The average N fertilizer application rate of 4 kg N ha^{-1} year^{-1} across the country from 1971 to 2000 (EarthTrends, 2003) and conventional tillage practice were assumed to remain through the 20th century.

2.3.2. Climate change scenarios for the 21st century

Following the IPCC Special Report on Emissions Scenarios (SRES), Hulme et al. (2001) developed an approach to evaluate the changes in both continental and regional seasonal-mean temperature and rainfall across the African continent by integrating new observed global climate data into several Global Climate Models, coupled with the Model for Greenhouse Induced Climate Change (Wigley et al., 2000). The Africa-focused Hulme's approach and its compliance with the IPCC SRES emissions scenarios made us believe that the simulation results under the climate change scenarios formulated by this approach should be comparable to those estimated from the approaches recommended in the IPCC Fourth Assessment Report (http://www.ipcc.ch/ipccreports/ar4-syr.htm).

Based on the data provided by the Ghana Environmental Protection Agency (2000) and the approach of Hulme et al. (2001), the climate change scenarios for the Assin district from 2000 to 2100 are assumed to have an increase in mean monthly temperature of 2.5 °C to 3.2 °C and a decrease in the annual precipitation by 10–21% by 2100 (Fig. 2). The scenarios included:

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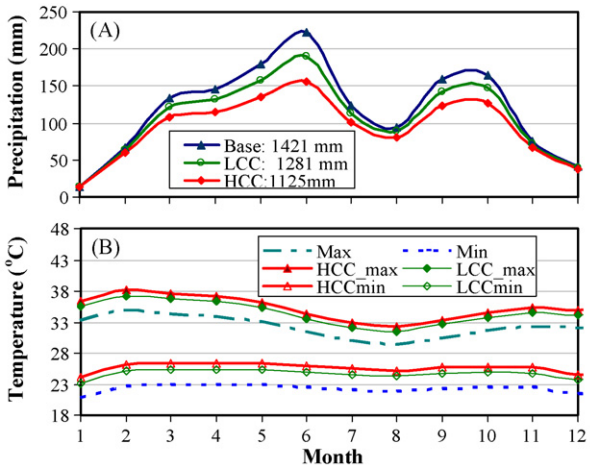

Fig. 2. Projected monthly precipitation and temperature in 2100 derived from the climate change scenarios from 2000 to 2100 for the Assin district.

(1) No climate change (NCC): the average values of precipitation and the minimum and maximum temperatures from 1971 to 2000 were assumed to remain the same for the 21st century.
(2) Low climate change (LCC): annual precipitation would gradually decrease 140 mm by 2100, and the mean minimum and maximum temperatures would increase by 2.5 °C and 2.4 °C, respectively.
(3) High climate change (HCC): precipitation would gradually decrease 296 mm by 2100, and the mean minimum and maximum temperatures would each gradually increase by 3.3 °C.

2.3.3. Nitrogen fertilization rates

The average N fertilizer application rate across the country from 1970 to 2000 was only about 4 kg N ha^{-1} year^{-1} (EarthTrends, 2003). According to the Crop Services Department of Ministry of Food and Agriculture of Ghana, the levels of fertilizers applied for maize production are recommended as follows: 120 kg ha^{-1} of compound fertilizer (consisting of nitrogen, phosphorus, and potassium) applied during planting, 120 kg ha^{-1} of ammonium sulfate ($(NH_4)_2SO_4$) for top dressing, and another 120 kg ha^{-1} of ammonium sulfate applied during tussling stage. The annual total fertilization rate recommended for maize production is about 60 kg N ha^{-1} year^{-1}. Liu et al. (2004a) documented that the N fertilization rate of 30 kg N ha^{-1} year^{-1} is usually applied on intensive and extensive croplands in south-central Senegal. Therefore, we set three N fertilization scenarios for all crops through the 21st century as follows:

(1) *N4*: The average N application rate of 4 kg N ha^{-1} year^{-1} from 1970 to 2000 was assumed to apply on all cropland from 2000 to 2100.
(2) *N30*: The N application rate will be increased to 30 kg N ha^{-1} year^{-1} after 2000.
(3) *N60*: The N application rate will be increased to 60 kg N ha^{-1} year^{-1} after 2000.

Model simulations for each N fertilization scenario were made with an assumption that there is no land use change in all the existing croplands.

2.3.4. Land use and land cover change scenario

The LULC scenario assumes that, by 2100, 50% of the existing degraded forest only will be gradually converted to cropland with about 20 trees ha^{-1}, while all the closed forest will be lawfully under protection and no change.

3. Results and discussion

We first simulated the initial ecosystem C status in 1900 and delineated the C dynamic spectrum for all the LULC types (see Table 1) from 1900 through 2000. Then, the C stocks in 2000 were used as baselines to predict their trends during the period from 2001 through 2100. The results of historical C dynamics during the 20th century are reported and discussed first.

3.1. Ecosystem C and SOC dynamics in the 20th century

The ecosystem C stock is considered the sum of live and dead above-ground and below-ground biomass C and SOC in the top 20 cm depth of soil. The data presented in Table 3 show that the total ecosystem C stock decreased from 305.8 Mg C ha^{-1} in 1900 to 152.8 Mg C ha^{-1} in 2000 over the whole study area. Such a significant reduction could be mainly attributed to the substantial removal of above-ground biomass by deforestation because the

Table 3
Consequences of climate change for ecosystem C budgets in the Assin district.

Land use/land cover	1900[a] (Mg ha^{-1})	2000 (Mg ha^{-1})	Change (%)	NCC		LCC		HCC	
				2100 (Mg ha^{-1})	Change (%)	2100 (Mg ha^{-1})	Change (%)	2100 (Mg ha^{-1})	Change (%)
Ecosystem C stock									
Closed forest	305.8 (71.3)	294.5 (29.3)	−3.7	295.9 (16.9)	0.5	298.4 (26.4)	1.3	295.0 (16.8)	0.2
Degraded forest		167.6 (58.7)		177.6 (28.6)	5.9	178.4 (39.4)	6.5	176.5 (28.0)	5.3
Cropland[b]		76.4 (15.9)		54.8 (10.9)	−28.3	51.6 (10.2)	−32.4	50.6 (11.1)	−33.7
All lands[c]	305.8 (35.5)	152.8 (20.0)	−50.0	145.7 (10.3)	−4.7	145.1 (10.5)	−5.0	143.3 (10.5)	−6.2
Soil C stock									
Closed forest	52.9 (2.3)	53.5 (10.6)	1.0	53.3 (1.8)	−0.2	52.2 (1.8)	−2.4	51.4 (1.8)	−3.9
Degraded forest	55.0 (4.2)	44.9 (3.0)	−18.4	43.4 (1.2)	−3.4	42.6 (1.2)	−5.3	42.1 (1.2)	−6.3
Cropland[b]	59.6 (5.4)	40.0 (9.7)	−32.9	31.4 (2.4)	−21.5	29.0 (2.3)	−27.5	28.6 (2.3)	−28.6
All lands[c]									
Slow SOC	30.1 (3.1)	20.8 (3.5)	30.9	17.3 (1.4)	−16.8	15.8 (1.3)	−23.9	15.4 (1.2)	−26.0
Passive SOC	21.6 (5.7)	21.7 (3.2)	0.7	20.8 (1.2)	−4.3	20.6 (1.2)	−5.2	20.5 (1.2)	−5.5
Total SOC	53.2 (8.6)	44.4 (5.1)	16.6	39.7 (1.9)	−10.5	38.1 (1.8)	−14.1	37.6 (1.7)	−15.2

NCC, no climate change; LCC, low climate change; HCC, high climate change; SOC, soil organic carbon stock in the top 20 cm depth; ecosystem C, the sum of live and dead above- and below-ground biomass C and SOC in the top 20 cm depth of soil.
[a] Assuming closed forest, but the initial SOC stock could be spatially different for the areas where the closed forest became either degraded forest or cropland afterwards.
[b] 4 kg N ha^{-1} year^{-1} is assumed to apply on all cropland.
[c] Weighted by the area of each land use/land cover type. The number in parentheses for each mean value is the standard deviation.

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Table 4
Responses of soil organic carbon (SOC) in croplands to climate change scenarios in the Assin district.

Nitrogen fertilization rate	2000 (Mg ha^{-1})	NCC		LCC		HCC	
		2100 (Mg ha^{-1})	Change[a] (%)	2100 (Mg ha^{-1})	Change[a] (%)	2100 (Mg ha^{-1})	Change[a] (%)
4 kg N ha^{-1}	40.0 (8.6)	31.4 (2.3)	−21	29.0 (2.3)	−28	28.6 (2.3)	−29
30 kg N ha^{-1}	40.0 (8.6)	33.8 (2.3)	−16	31.5 (2.3)	−21	30.9 (2.3)	−23
60 kg N ha^{-1}	40.0 (8.6)	35.6 (2.5)	−11	33.6 (2.6)	−16	32.9 (2.5)	−18

NCC, no climate change; LCC, low climate change; HCC, high climate change.
[a] Change percentage in SOC from 2000 to 2100. The numbers in parentheses are the standard deviation.

living biomass was reduced by 144.2 Mg C ha^{-1} by 2000. The reduction in living biomass accounted for 94% of the reduction in the total ecosystem C stock, higher than the reduction rate (88%) estimated by Liu et al. (2004a) for south-central Senegal.

During the same period, the SOC stock declined from 53.2 Mg C ha^{-1} to 44.4 Mg C ha^{-1}, which contributed about 6% to the total ecosystem C loss. For individual LULC types, by the year 2000, there was a small SOC gain (0.6 Mg C ha^{-1}) within the closed forest, a loss of 10.1 Mg C ha^{-1} from the degraded forest, and a significant reduction from 59.6 Mg C ha^{-1} to 40.0 Mg C ha^{-1} from all cropland (representing a C source strength of 196 kg C ha^{-1} year^{-1}). The SOC reduction of 33% from cropland was directly associated with cultivation-enhanced emissions after deforestation of both closed forest and degraded forest. The estimates of SOC losses from the conversion of forest to croplands generally range from 20% to 40% in various ecosystems (e.g., DeFries et al., 2002; Guo and Gifford, 2002; Houghton, 2003; Houghton and Hackler, 2006; Liu et al., 2004a; Tan et al., 2009). As Houghton (2003) concluded, deforestation is the largest contributor to tropical land use emissions.

Based on resistance to decomposition, SOC stock is usually thought to consist of labile, slow, and passive pools (Parton et al., 1987). Of the total SOC stock, the labile pool comprises 5–10%, and both the slow and passive pools together account for 90–95%. Our simulation results show that the loss of the slow pool from cropland amounted to 31%, while the passive pool was marginally in balance (see Table 3). In other words, the loss of the total SOC stock was mostly from the slow C pool.

3.2. Ecosystem C and SOC change trends during the 21st century

As presented in Table 3, if there are no changes in LULC and land management and the N fertilization rate of 4 kg N ha^{-1} remains for the cropland through the 21st century, the ecosystem C stock would decrease by 4.7% under NCC and 6.2% under HCC for the whole study area. This reduction would be totally attributed to the C loss from the cropland. The losses of SOC for the district would continue through the 21st century and amount 10.5% under NCC and 15.2% under HCC. Soils under all kinds of lands tend to become C sources under LCC and HCC, but the rates would vary with LULC type and the warming and drying stress as assumed for climate change scenario in this study. The closed forest soils would nearly remain C balanced under NCC and be a small C source under LCC and HCC. The degraded forested soils would remain C sources; however, the strength would be much smaller, decreasing from 100 kg C ha^{-1} year^{-1} in the 20th century to 15 kg C ha^{-1} year^{-1}, 23 kg C ha^{-1} year^{-1}, and 28 kg C ha^{-1} year^{-1} under NCC, LCC, and HCC over the 21st century, respectively. However, the trend of significant SOC emissions from the cropland in the 20th century would continue through the 21st century regardless of climate change scenarios, and the greatest source strength of 114 kg C ha^{-1} year^{-1} would occur under HCC (86 kg C ha^{-1} year^{-1} under NCC). It seems that the dynamics of SOC budgets (particularly in the cropland) are more sensitive to the climate change than above-ground biomass formation.

3.3. Role of N fertilization in mitigating C emissions from cropland

The results presented in Table 4 show that an increase in N fertilization rate from the current rate to either 30 kg N ha^{-1} year^{-1} or 60 kg N ha^{-1} year^{-1} significantly enhances C sequestration in soil (or mitigates cultivation-induced C emissions from soil). In comparison to the C emissions with the current N fertilization rate, the average reduction in C emissions would be about 6% with 30 kg N ha^{-1} year^{-1} and 10% with 60 kg N ha^{-1} year^{-1} under all climate change scenarios. As indicated in Fig. 3, this kind of change could be dominantly attributed to the reduction in the slow SOC pool (of the total loss, about 75% from the slow pool, 9% from the passive pool, and 16% from the labile pool). The role of N fertilization, however, could be partially counterbalanced by the adverse impact of progressive warming and drying stress.

3.4. Responses of crop yields to nitrogen fertilizer under projected climate scenarios

Fig. 4 illustrates that the response of crop yield to N fertilization rate depends mainly on crop species but is not significantly influenced by climate warming and drying stresses. Generally,

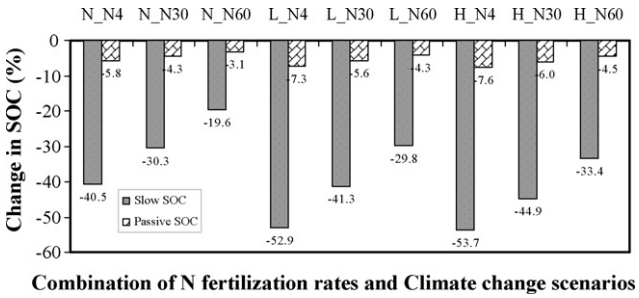

Fig. 3. Variations of SOC pools in croplands responding to nitrogen fertilization under different climate change scenarios from 2000 to 2100 (N, L, and H refer to no, low, and high climate change scenario, respectively; N4, N30, and N60 represent nitrogen fertilization rates of 4 kg N ha^{-1} year^{-1}, 30 kg N ha^{-1} year^{-1}, and 60 kg N ha^{-1} year^{-1}, respectively).

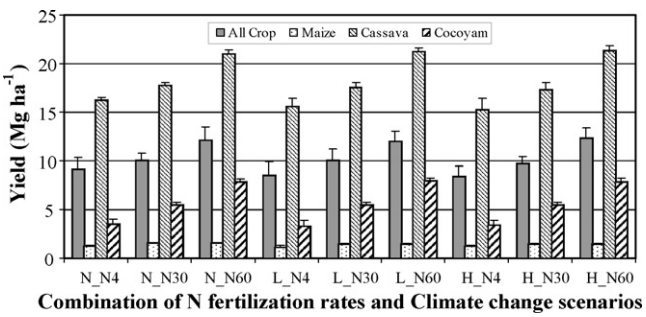

Fig. 4. Average grain yields associated with nitrogen fertilization and climate change scenarios during the 21st century in the Assin district (see Fig. 3 for scenario labels. Error bars refer to standard deviation).

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Table 5
Change percentage of C stocks following the conversion of 50% of the degraded forest to cropland from 2000 to 2100 in Assin district.

Scope		Ecosystem C			SOC		
		NCC (Mg ha^{-1})	LCC (Mg ha^{-1})	HCC (Mg ha^{-1})	NCC (Mg ha^{-1})	LCC (Mg ha^{-1})	HCC (Mg ha^{-1})
Changed area	Degraded forest (DF)	6	7	6	0	−2	−3
	DF-derived cropland[a]	−42	−44	−46	−24	−30	−31
Whole area	Without change[b]	−5	−5	−6	−10	−14	−15
	With change[c]	−14	−14	−16	−14	−18	−19

[a] 4 kg N ha$^{(1}$ year^{-1} is assumed to apply on all cropland.
[b] No land cover change through the 21st century.(refer to Table 3).
[c] Assuming 50% of the area of degraded forest in 2000 would be converted to cropping systems by 2100. NCC, LCC, and HCC refer to no, low, and high climate change scenarios, respectively.

under the same climate conditions, to increase the N fertilization rate would significantly increase crop yield. For instance, there would be an increase in crop yield by 10% with N30 and 32% with N60 under NCC, accordingly, 17% and 40% under LCC, and 15% and 45% under HCC. But there would be no significant differences between LCC and HCC, even for individual crop species. Of the three crops, cocoyam shows the strongest response to N fertilization under all climate change scenarios, especially under LCC, with a grain yield increase of 64% with N30 and 141% with N60.

3.5. Impacts of deforestation on ecosystem C budgets during the 21st century

As of 2000, 34.1% of the total land area was defined as degraded forest (Table 1). If 50% of degraded forest area is converted to cropland by 2100, the ecosystem C stock in the degraded forest-derived cropland would decrease by about 42% under NCC, 44% under LCC, and 46% under HCC (Table 5). SOC losses from this kind of cropland would amount up to 24%, 30%, and 31%, respectively, whereas SOC losses from the degraded forest could be only 0%, 2%, and 3%, respectively. Consequently, for the whole study area, the ecosystem C losses are about 9% more with land cover change than without land cover change, accordingly, the SOC losses are 4% more (calculated from the numbers presented in the bottom two rows in Table 5). The SOC loss would be 2.0–2.5% higher from the new cropland (Table 5) than from the old cropland (see Table 4 with 4 kg N ha^{-1} fertilization rate). This increased SOC loss can be attributed to higher antecedent SOC stock level in the degraded forest-derived cropland (44.9 Mg C ha^{-1} in the new cropland, while 40.0 Mg C ha^{-1} in the old cropland in 2000), and the actual rates of C emissions would be as high as 110 kg C ha^{-1} year^{-1} under NCC and 140 kg C ha^{-1} year^{-1} under both LCC and HCC.

4. Conclusion

The trend of significant C emissions from the forest-derived cropland in the 20th century would continue through the 21st century regardless of climate change scenario but can be partially offset by N fertilization. Lack of N replenishment for soil N depletion would be the major constraint on crop production in the future. To increase N fertilizer input would be one of vital adaptive measures to ensure food security and maintain agricultural sustainability through the 21st century even though the effect of the fertilization on enhancing C sequestration could be largely offset by the adverse impact of progressive warming and drying stresses. Meanwhile current cropping systems can be optimized to fully use the rainfall resource in the study area. The LULC changes have a stronger influence on ecosystem C budgets than the projected climate change scenarios in the study area.

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References

DeFries, R.S., Houghton, R.A., Hansen, M.C., Field, C.B., Skole, D., Townshend, J., 2002. Carbon emissions from tropical deforestation and regrowth based on satellite observations for the 1980s and 1990s. Proceedings of the National Academy of Sciences U.S.A. 99, 14256–14261.
EarthTrends, 2003. EarthTrends Country Profile, available at http://earthstrends.-wri.org/.
Field, C.B., Lobell, D.B., Peters, H.A., Chiariello, N.R., 2007. Feedbacks of terrestrial ecosystems to climate change. Annual Review of Environment and Resources 32, 1–29.
Ghana Environmental Protection Agency (EPA), 2000. Ghana's Initial National Communication under the United Nations Framework Convention on Climate Change. EPA, Ghana, p. 160.
Gonzalez, P., 2001. Desertification and a shift of forest species in the West African Sahel. Climate Research 17, 217–228.
Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345–360.
Houghton, R.A., 2003. Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus Series B: Chemical and Physical Meteorology 55, 378–390.
Houghton, R.A., Hackler, J.L., 2006. Emissions of carbon from land use change in sub-Saharan Africa. Journal of Geophysical Research 111, G02003.
Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1900–2100. Climate Research 17, 145–168.
Laurance, W., 2004. Forest–climate interactions in fragmented tropical landscapes. Philosophical Transactions of the Royal Society of London Series B 359, 345–352.
Liu, S., Kairé, M., Wood, E., Dialloc, O., Tieszen, L.L., 2004a. Impacts of land use and climate change on carbon dynamics in south-central Senegal. Journal of Arid Environments 59, 583–604.
Liu, S., Loveland, T.R., Kurtz, R.M., 2004b. Contemporary carbon dynamics in terrestrial ecosystems in the southeastern plains of the United States. Environmental Management 33, S442–S456.
Nicholson, S.E., 2001. Climatic and environmental change in Africa during the past two centuries. Climate Research 17, 123–144.
Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grasslands. Soil Science Society of American Journal 51, 1173–1179.
Paustian, K., Robertson, G.P., Elliott, E.T., 1995. Management impacts on carbon storage and gas fluxes (CO_2, CH_4) in mid-latitude cropland and grassland ecosystems. In: Lal, R., Kimble, J., Levine, E., Stewart, B.A. (Eds.), Soil Management and Greenhouse Effect. Advances in Soil Science. Lewis Publishers, Boca Raton, FL, pp. 69–84.
Tan, Z., Tieszen, L.L., Tachie-Obeng, E., Liu, S., Dieye, A.M., 2009. Historical and simulated ecosystem carbon dynamics in Ghana: land use, management, and climate. Biogeosciences 6, 45–58.
Wigley, T.M.L., Raper, S.C.B., Salmon, M., Hulme, M., 2000. MAGICC: Model for the Assessment of Greenhouse-gas Induced Climate Change, version 2.4. Climatic Research Unit, Norwich, UK.
Woomer, P.L., Toure, A., Sall, M., 2004. Carbon stocks in Senegal's Sahel transition zone. Journal of Arid Environments 59, 499–510.