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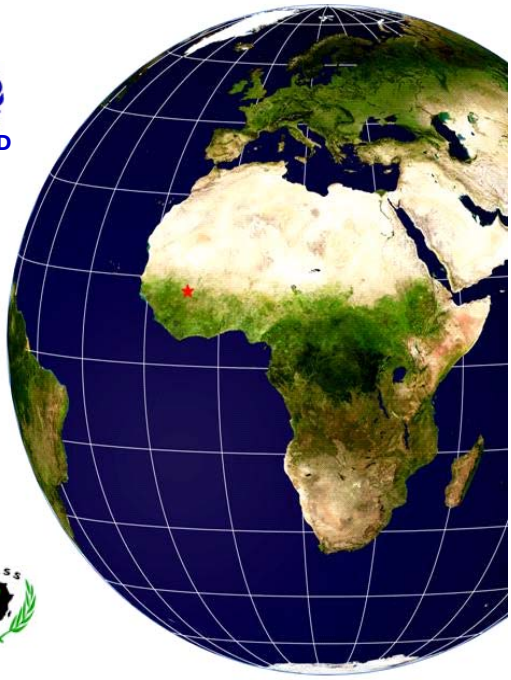

Prepared by Larry L. Tieszen
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5	Corresponding Author	Family Name	**Tan**
6		Particle	
7		Given Name	**Zhengxi**
8		Suffix	
9		Organization	ARTS, U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center
10		Division	
11		Address	47914 252nd Street, Sioux Falls 57198, SD, USA
12		e-mail	ztan@usgs.gov
13	Author	Family Name	**Tieszen**
14		Particle	
15		Given Name	**Larry L.**
16		Suffix	
17		Organization	ARTS, U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center
18		Division	
19		Address	47914 252nd Street, Sioux Falls 57198, SD, USA
20		e-mail	
21	Author	Family Name	**Liu**
22		Particle	
23		Given Name	**Shuguang**
24		Suffix	
25		Organization	ARTS, U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center
26		Division	
27		Address	47914 252nd Street, Sioux Falls 57198, SD, USA
28		Organization	South Dakota State University
29		Division	Geographic Information Science Center for Excellence
30		Address	Brookings 57007, SD, USA
31		e-mail	
32		Family Name	**Tachie-Obeng**

33	Author	Particle	
34		Given Name	**Emmanuel**
35		Suffix	
36		Organization	Ghana Environmental Protection Agency
37		Division	
38		Address	Accra , Ghana
39		e-mail	

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43 Abstract

Many savannas in West Africa have been converted to croplands and are among the world's regions most vulnerable to climate change due to deteriorating soil quality. We focused on the savanna-derived cropland in northern Ghana to simulate its sensitivity to projected climate change and nitrogen fertilization scenarios. Here we show that progressive warming–drying stress over the twenty-first century will enhance soil carbon emissions from all kinds of lands of which the natural ecosystems will be more vulnerable to variation in climate variables, particularly in annual precipitation. The carbon emissions from all croplands, however, could be mitigated by applying nitrogen fertilizer at 30–60 kg N ha^{-1} $year^{-1}$. The uncertainties of soil organic carbon budgets and crop yields depend mainly on the nitrogen fertilization rate during the first 40 years and then are dominated by climate drying stress. The replenishment of soil nutrients, especially of nitrogen through fertilization, could be one of the priority options for policy makers and farm managers as they evaluate mitigation and adaptation strategies of cropping systems and management practices to sustain agriculture and ensure food security under a changing climate.

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Modeling to evaluate the response of savanna-derived cropland to warming–drying stress and nitrogen fertilizers

Zhengxi Tan · Larry L. Tieszen · Shuguang Liu · Emmanuel Tachie-Obeng

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Abstract Many savannas in West Africa have been converted to croplands and are among the world's regions most vulnerable to climate change due to deteriorating soil quality. We focused on the savanna-derived cropland in northern Ghana to simulate its sensitivity to projected climate change and nitrogen fertilization scenarios. Here we show that progressive warming–drying stress over the twenty-first century will enhance soil carbon emissions from all kinds of lands of which the natural ecosystems will be more vulnerable to variation in climate variables, particularly in annual precipitation. The carbon emissions from all croplands, however, could be mitigated by applying nitrogen fertilizer at 30–60 kg N ha^{-1} $year^{-1}$. The uncertainties of soil organic carbon budgets and crop yields depend mainly on the nitrogen fertilization rate during the first 40 years and then are dominated by climate drying stress. The replenishment of soil nutrients, especially of nitrogen through fertilization, could be one of the priority options for policy makers and farm managers as they evaluate mitigation and adaptation strategies of cropping systems and management practices to sustain agriculture and ensure food security under a changing climate.

Z. Tan (✉) · L. L. Tieszen · S. Liu
ARTS, U.S. Geological Survey (USGS)
Earth Resources Observation and Science (EROS) Center,
47914 252nd Street, Sioux Falls, SD 57198, USA
e-mail: ztan@usgs.gov

S. Liu
Geographic Information Science Center for Excellence,
South Dakota State University, Brookings, SD 57007, USA

E. Tachie-Obeng
Ghana Environmental Protection Agency, Accra, Ghana

Q1

1 Introduction

Savannas are globally important ecosystems vital to human economies (Sankaran et al. 2005). They cover one-fifth of the earth's land surface and support a large proportion of the world's population and most of the livestock and wild herbivore biomass (Scholes and Archer 1997). Savannas in Africa are usually characterized by the co-dominance of trees and grasses. Over time, many of these ecosystems have been converted to croplands. Both natural savanna and savanna-derived cropland have become sensitive to land surface disturbances (such as mining and agricultural expansion from natural savanna, and intensification of cropping and management practices) and are among the world's regions most vulnerable to climate change (Sala et al. 2000; Bond et al. 2003; Weltzin and McPherson 2003). Deterioration of soil fertility and decrease in crop yields on this kind of cropland due to population pressure-induced cropping intensification is threatening food security and human livelihoods (Sankaran et al. 2005). For example, the annual population growth rate from 2000 to 2008 in Ghana was about 2.81% (http://www.statsghana.gov.gh/), while the annual food increase rate was only about 1.26% (http://faostat.fao.org/). In our study area presented here, Bawku district, the population density (capital per square kilometer) increased from 111 in 1970 and 160 in 1984 to 300 in 2000 (http://www.statsghana.gov.gh/).

The availability of water and nutrients and the regime of land disturbances are generally thought to be critical in regulating savanna ecosystem performance. For natural savannas, water availability determines the coexistence of woody cover and grass (Sankaran et al. 2005). Most African savannas receive an annual precipitation of about 650 ± 134 mm, and if the annual precipitation is greater than the upper limit $650 + 134$ mm, there is sufficient water available for natural savanna systems to build up woody canopy (Sankaran et al. 2005). However, many natural savannas in sub-Saharan Africa have been cultivated for food production and most natural trees and grass have been replaced with crops. We need to understand the responses of such managed ecosystems to changes in climate and crop management so that adaptive management policies can be established to ensure sustainability of the savanna-derived croplands under varying climates.

Ghana is a very diverse country physically and culturally and usually characterized by its unique ecological regions, or ecoregions (Allotey and Tachie-Obeng 2006). There are remarkable gradients of climatic variables. With a decrease in precipitation and increase in temperature from the south to the north across Ghana territory, accordingly, ecoregions have been characterized with the moist forest-dominated ecosystem in the south to those with savanna in the north, and the transitional zone is in central Ghana.

In response to climate change, the changes in the distribution and dominance of different species and constraints from soil nutrient availability (Hungate et al. 2003; Luo et al. 2006; Reich et al. 2006b) could make the savanna-derived cropping ecosystem different from natural savannas. Particularly, the soil nitrogen (N) depletion from croplands in sub-Saharan Africa has been documented ranging from 11 to 22 kg N ha^{-1} $year^{-1}$ (and 1.3–2.5 kg K ha^{-1} $year^{-1}$ and 7.5–15 kg P ha^{-1} $year^{-1}$) since the 1950s (Lal 2007). The average N fertilizer application rate for crops across Ghana from 1970 to 2000 was about 4 kg N ha^{-1} $year^{-1}$ (EarthTrends 2003). The continuing nutrient depletion has been perpetuated with an attendant decline in soil productivity

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(Lal 2007). If limitations to land productivity resulting from the insufficient supply of N nutrient are widespread in both natural and managed ecosystems, soil N supply likely becomes a critical constraint on global terrestrial responses to climate warming (Oren et al. 2001; Hungate et al. 2003; Luo et al. 2006; Reich et al. 2006a, b). In this study, the land use change data, historical climate records, and soil inventory are used to drive a biogeochemical model for simulating the dynamics of ecosystem C budgets in the Bawku savanna zone of Ghana during the twentieth century, and then from the baselines we evaluate the sensitivity of soil organic C (SOC) stocks and crop yields to the projected progressive warming–drying and N fertilization scenarios over the twenty-first century.

2 Materials and methods

2.1 Study area

The Bawku savanna zone is in the northeastern corner of Ghana, West Africa, and covers an area of 2,130 km^2. We assumed the whole area in 1900 was covered with the open forest. According to remotely sensed imagery in 2000, most of the open forest was deforested to become the savanna, one of eastern Sudan savanna ecosystems as defined by Allotey and Tachie-Obeng (2006). As a result, the open forest was only 0.4%, grass/herb lands accounted for 16.7%, while the croplands (or cultivated savanna) amounted up to 79%. The mean annual minimum and maximum temperatures between 1971 and 2000 across the study area were 22.6 ± 0.4°C and 31.9 ± 1.6°C, respectively. The mean annual precipitation was $1{,}008 \pm 143$ mm, about 90% of which was in the period from April through October. According to the field observations, major crop species are groundnut (*Arachis hypogaea*), sorghum (*Sorghum bicolor* S.), millet (*Pennisetum glaucum* P.), rice (*Oryza glaberrima*), and maize (*Zea mays* L.). Unpublished local government's statistics showed that these cropping systems accounted for 29%, 36%, 20%, 13%, and 2% of all the planted area in 2000, respectively.

2.2 Modeling system and simulations

GEMS (refer to Liu et al. 2004 for details), a biogeochemical modeling system, was used in this study to simulate C and N dynamics within each ecosystem. GEMS has the capability of modeling the impacts of land surface disturbances and management practices, including land use and land cover change, fertilization, cultivation, and natural disturbances (Liu et al. 2004). In order to reduce the potential biases resulted from the direct injection of information contained in spatial databases that are aggregated to map unit level from inputs (Reiners et al. 2002), GEMS uses data Q2 assimilation mechanisms to incorporate field scale spatial heterogeneities of state and driving variables into simulations in two steps: searching and retrieving relevant information from various databases according to the keys provided by a joint frequency distribution (JFD) table, and then downscaling the aggregated information at the map unit level to the field scale using a Monte Carlo approach. Once all input data are assimilated, they are incorporated into the modeling processes by means of the input/output processor (IOP) and updated with assimilated data. Values of selected

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output variables are written by the IOP to a set of output files after each model execution. The geospatial GIS layers and other attribute data used in modeling are briefly summarized in Section 2.3.

The architecture of GEMS in this study was designed for three scenarios: initial C status around 1900 when all land was assumed to cover with open forest (Allotey and Tachie-Obeng 2006), 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, ecosystem C fluxes and SOC stocks in 1900 were assumed to be in equilibrium and quantified by running GEMS for 1,500 years under natural vegetation. The field observation data of SOC stocks and crop yields of 20 sampling sites across the study area were used for model parameterization and validation of model outputs. The results for 2000 were set as the baselines for simulating SOC dynamics and crop yield variations for the twenty-first century under the climate change and N fertilization scenarios described below.

2.3 Input data for model simulations

The geospatial datasets used in GEMS include LULC images for 1972, 1986, and 2000 provided by Ghana Environmental Protection Agency and Center for Remote Sensing and Geographical Information System, soil inventory taken from the FAO soil database, and historical climate records from 1971 to 2000 (including mean monthly precipitation, mean monthly minimum- and maximum temperatures). Overlaying these geographic information system (GIS) layers generates a combined GIS coverage (i.e. JFD layer) and a JFD table. The JFD layer defines the spatial association or covariance of these variables and represents the spatial heterogeneities Q2 of biophysical variables across the study area (Liu 2009). Each JFD case (i.e. a grid) will be the spatial simulation unit of GEMS. A JFD table lists all of the realized unique combinations of the values of the variables and their associated frequencies (or areas), thereby providing the spatial framework to visualize and analyze simulation results, such as the spatial and temporal patterns of biogeochemical properties Q2 (Liu 2009).

The information about land use and land cover, climate variables, and carbon stocks in vegetation and soils as of 2000 were used as the baselines for simulations for the twenty-first century.

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 Tables 1,

Q3 **Table 1** Percentage of each crop in all planted area (crop composition) across Bawku district

Period	Open cultivated savanna[a]					Widely open cultivate savanna[b]				
	Maize	Sorghum	Millet	Rice	Groundnut	Maize	Sorghum	Millet	Rice	Groundnut
1900–1975	1	13	13	1	22	1	17	8	5	19
1976–1982	1	14	12	1	22	1	17	9	4	19
1983–1986	1	15	10	3	21	1	16	8	5	20
1987–1994	1	15	9	5	20	1	16	9	4	20
1994–2000	1	15	9	6	19	1	15	9	6	19

[a]With ten to 20 trees per hectare
[b]With less than ten trees per hectare

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Table 2 Probabilities of crop rotation

	Maize	Sorghum	Millet	Rice	Groundnut
Maize	0.45	0.15	0.20	0.00	0.20
Sorghum	0.15	0.40	0.25	0.00	0.20
Millet	0.20	0.20	0.35	0.00	0.25
Rice	0.00	0.00	0.00	1.00	0.00
Groundnut	0.20	0.25	0.20	0.00	0.35

2, 3 and 4. An average level of 2 Mg ha^{-1} $year^{-1}$ manure as suggested by field investigation was assumed to add to all croplands for modeling. The traditional plowing methods (hand- and animal-driven plowing) were applied to define tillage parameter but no differences between both were defined for model simulation in this study. The frequency of fuelwood production from woodlands was assumed to be one time each year with a removal of 25% aboveground biomass. Such management information was retrieved by GEMS based on the JFD table and other "instruction" files prepared for this study. All information of management practices addressed above was synthesized from sample site investigations in 2006 and literature.

Soil organic C accumulation is closely related to the amount of biomass production which varies with land use type and individual crop species. While, the amount of biomass contributed to SOC budget also depend up the crop composition, crop rotation, fallow schedule, and harvesting methods. For example, more trees grown in cropland will have more annual biomass and therefore will make more contribution to SOC budget. GEMS is facilitated with special algorithms to simulate the impacts of each management practice on SOC budget.

2.4 Climate change scenarios

The climate change scenarios in the twenty-first century were assumed as follows:

(1) No Climate Change (NCC): the average values of precipitation and minimum and maximum temperatures from 1971 to 2000 are assumed to remain the same for the twenty-first century.
(2) Low Climate Change (LCC): the precipitation during the growing season (from April through October) will decrease by 105 mm by 2100, and the annual minimum and maximum temperatures will increase by 3.1°C and 2.6°C, respectively.
(3) High Climate Change (HCC): similar to LCC, the annual precipitation will decrease by 240 mm by 2100, and the minimum and maximum temperature will increase by 4.7°C and 3.8°C, respectively.

The approach of Hulme et al. (2001) and the climate records between the 1971 and 2000 from Ghana EPA (2000) were used to formulate the scenarios above.

Table 3 Fallow schedule

Land use type	Years in fallow		Years in cropping	
	Minimum	Maximum	Minimum	Maximum
Open cultivated savanna	1	2	5	10
Widely open cultivated savanna	1	3	4	8

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Q3 **Table 4** Percentage of harvested area associated with harvesting options

Period	GH	G50	G
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

HG harvesting all grain and stalk, *G50* harvesting grain and 50% of stalk, *G* harvesting grain only

Because Hulme's approach was developed for Africa and complied with the IPCC SRES emissions scenarios, we assumed 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).

2.5 Nitrogen (N) fertilization rates for the twenty-first century

The average N fertilizer application rate across the country from 1971 to 2000 was only about 4 kg N ha^{-1} $year^{-1}$ (http://earthtrends.wri.org/). Crop Services Department of Ministry of Food and Agriculture of Ghana recommended an annual total fertilization rate of about 60 kg N ha^{-1} $year^{-1}$ for maize production, consisting of 120 kg ha^{-1} of compound fertilizer (N, P, and K at 15–15–15% ratio) and 240 kg ha^{-1} of ammonium sulfate ($(NH_4)_2SO_4$, containing about 20% N) for (Communication with Tachie-Obeng, Ghana EPA). Liu et al. (2004) documented the average N fertilization rate of 30 kg N ha^{-1} $year^{-1}$ applied on all croplands in south-central Senegal. Therefore, we set three N fertilization scenarios for all crops through the twenty-first century as follows:

(1) N4: the average N application rate of 4 kg N ha^{-1} $year^{-1}$ from 1970 to 2000 (EarthTrends 2003) is assumed to apply on all cropland until 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.

3 Results and discussion

In order to assess the impacts of future climate change on ecosystem C dynamics during the twenty-first century, we first set up the C baselines (as of 2000) by running GEMS with historical climate records and an average N fertilization rate from 1971 to 2000. Our simulation results show that, accompanying a substantial reduction in ecosystem C stock (here, the ecosystem C stock is defined as the sum of live and dead above- and below-ground biomass C, and SOC in the top 20 cm soil layer) from 131 Mg C ha^{-1} in 1900 to 36 Mg C ha^{-1} in 2000, the SOC stock declined from 33.4 to 19.4 Mg C ha^{-1} in all croplands. From these baselines, we simulated the responses of SOC stocks and crop yields to the climate change scenarios through the twenty-first century with an assumption of no change in land use and management.

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Table 5 Consequences of climate change to soil carbon stocks in Bawku district Q3

Land use and land cover	2000		NCC		LCC		HCC	
	Area %[a]	SOC Mg C ha^{-1}	2100 Mg C ha^{-1}	Change %	2100 Mg C ha^{-1}	Change %	2100 Mg C ha^{-1}	Change %
Open forest	0.4	28.3	23.9	−16	22.6	−20	22.0	−22
Open savanna	2.3	22.9	20.3	−11	19.0	−17	18.4	−20
Riverine	1.5	30.5	28.7	−6	27.2	−11	26.4	−13
Grass/herb	16.7	18.3	15.0	−18	13.9	−24	13.4	−27
Cropland[b]	79.0	19.4	21.1	9	19.8	2	19.4	0
Settlements	0.3							
Average		19.9	20.1	1	18.9	−5	18.5	−7

NCC no climate change, *LCC* low climate change, *HCC* high climate change
[a]Percentage of the total land area
[b]With an existing nitrogen fertilization rate (4 kg N ha^{-1} year^{-1})

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3.1 Trends of SOC dynamics in response to climate change and N fertilization

The data presented in Table 5 indicate that, by 2100, there will be a SOC sink of 1.70 and 0.36 Mg C ha^{-1} under the no climate change (NCC) and the low climate change (LCC), respectively, and little change will take place under the high climate change (HCC). On the other hand, a substantial reduction in SOC stock (about 20%) will occur in all savannas (Table 5). Such difference can be attributed to the changes in the dominance of different species and life forms between the natural and managed ecosystems (Field et al. 2007) and differences in management practices. Clearly, open savanna ecosystems are naturally dominated by trees and grass and vulnerable to the progressive warming–drying stress which could enhance soil respiration by about 20% (Rustad et al. 2001). However, agricultural lands are grown with various crops (see Table 6) and managed with measures such as fertilization, weed control, irrigation, etc. to mitigate the impacts of the progressive climate stress on biomass production, and in turn the increased above- and below-ground biomass production can compensate some SOC loss caused by warming–drying-enhanced decomposition

Table 6 Average crop yields over the twenty-first century associated with N fertilization and climate change scenarios Q3

Crop	Area[a]	Base[b]	N_N4	N_N30	N_N60	L_N4	L_N30	L_N60	H_N4	H_N30	H_N60
	%	Mg ha^{-1} year^{-1}									
Maize	2.3	1.13	1.25	1.28	1.28	1.14	1.16	1.16	1.07	1.08	1.09
Sorghum	36.0	0.92	1.07	1.21	1.24	0.97	1.06	1.07	0.90	0.97	0.99
Millet	20.0	0.82	0.98	1.19	1.23	0.92	1.04	1.07	0.85	0.96	0.99
Rice	12.5	2.50	2.71	3.75	4.05	2.85	3.57	3.80	2.87	3.47	3.62
Groundnut	29.1	1.01	1.07	1.06	1.07	0.71	0.71	0.71	0.60	0.61	0.60
Mean[c]		1.13	1.26	1.48	1.54	1.12	1.27	1.31	1.05	1.18	1.21
Change %			11.8	31.3	36.6	−0.7	12.5	16.0	−6.5	4.4	7.1

N no climate change scenarios, *L* low climate change scenarios, *H* high climate change scenarios, *N4* nitrogen fertilizer levels of 4 kg N ha^{-1} year^{-1}, *N30* nitrogen fertilizer levels of 30 kg N ha^{-1} year^{-1}, *N60* nitrogen fertilizer levels of 60 kg N ha^{-1} year^{-1}
[a]Percentage of all planted area
[b]Grain yield of dry biomass averaged from 1972 to 2000
[c]Area–weight average

of soil organic matter. That may be the major reason why open savanna ecosystems are more sensitive to climate change and show a trend of SOC loss over time under warming–drying conditions.

It can be seen from the table appended to Fig. 1 that increasing N fertilization rate will significantly enhance SOC accumulation, especially under NCC. The fertilization rates of N4, N30, and N60 will lead to an increase in SOC stock by 9.4%, 18.3%, and 21.6% by the year 2100, respectively. Meanwhile, the soil organic nitrogen (SON) budgets show a stronger positive response to N fertilization than do SOC budgets (see Fig. 1b).

Prior to 2000, the SOC dynamics were principally caused by cultivation-induced C emissions from soil. As illustrated in Fig. 1a, an increase in N fertilization will enhance SOC sequestration, depending on the warming–drying stress. The positive effects of N fertilization on SOC accumulation will be eventually offset by C emissions that are induced by warming–drying stress. Figure 1 also suggests that the SOC budget in croplands will be determined by the N fertilization rate for the first 40 years and then will be dominated by climate variables. If no climate change (or NCC), there are very little changes in SOC stock after about the 40-year point for both N30 and N60 fertilization scenarios, which could be interpreted as the SOC reaching a new equilibrium after 40 years. While, the SOC stocks will decline with increased progressive warming–drying stress over time, especially under HCC, which implies that SOC accumulation rate with N fertilization will become weaker after about 40 years so as to be unable to offset the increased SOC emissions under the projected climate change scenarios. A similar trend will happen to SON (see Fig. 1b).

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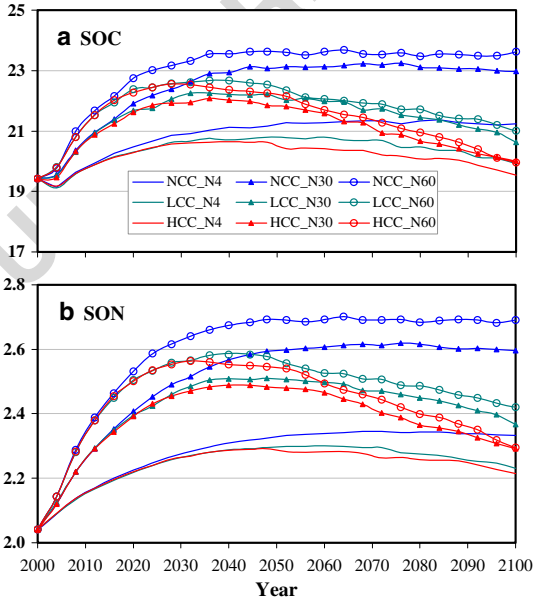

Combined Scenario	Change % 2000-2100	
	SOC	SON
NCC_N4	9.4	14.3
NCC_N30	18.3	27.2
NCC_N60	21.6	31.8
LCC_N4	2.6	9.3
LCC_N30	6.2	16.0
LCC_N60	8.1	18.6
HCC_N4	0.6	8.5
HCC_N30	2.9	12.3
HCC_N60	2.7	12.5

Fig. 1 Simulated responses of soil organic carbon (SOC) and soil organic nitrogen (SON) stocks in all cropping systems to N fertilization levels under climate change scenarios for the twenty-first century (*NCC*, *LCC*, and *HCC*, no climate change, low and high climate change scenarios, respectively; *N4*, *N30*, and *N60*, fertilization level of 4, 30, and 60 kg N ha^{-1} $year^{-1}$, respectively)

Note that even with business-as-usual fertilization level (N4), the SOC and SON stocks still show an increasing trend over time under all climate change scenarios (Fig. 1). There are probably two reasons: (1) N deposition, and (2) crop rotations except rice as shown in Table 2. It was assumed that there will be precipitation-dependent N deposition at an average rate of about 1.3 kg N ha^{-1} $year^{-1}$ (if annual precipitation is 1,000 mm) which was set for model simulations. Meanwhile, groundnut is a kind of N-fixation crop and can increase soil N content, and any rotation of other cropping systems with groundnut planted area will increase soil N availability to next crop growth. Besides N fertilization, both external N sources will enhance SOC sequestration and SON accumulation, especially under a combination of NCC and N4 scenarios.

3.2 Responses of crop yields to changes in climate and N fertilization

Compared with the average from 1972 to 2000 (Table 6), grain yield averaged through the twenty-first century will increase by 11.8% with the existing fertilization rate (4 kg N ha^{-1} $year^{-1}$, or N4) under NCC, but decrease by 0.7% and 6.5% under LCC and HCC, respectively. Such adverse impacts can be significantly mitigated by increasing the N fertilization rate, especially under LCC. For example, to raise the N fertilization rate from 4 to 30 kg N ha^{-1} $year^{-1}$ under LCC will lead to a grain yield increase of 90 kg ha^{-1} for sorghum, 120 kg ha^{-1} for millet, 720 kg ha^{-1} for rice, but little change for maize and a decline over time for groundnut. The sensitivity of crop grain yields to N fertilizers also depends on the extent of warming–drying stress as illustrated in Fig. 2. An increment in the N fertilization rate from 4 kg N ha^{-1} $year^{-1}$ to either 30 or 60 kg N ha^{-1} $year^{-1}$ will significantly increase grain yields of all crops (except groundnut) until about 2040, then the efficiency of N fertilizer will decline, especially under HCC. The declining efficiency of N fertilizers over time may be also related to deficiencies of other nutrients such as phosphorus (Buresh et al. 1997) and potassium (Alber et al. 1997).

Interestingly, Fig. 2 demonstrates an increase in crop yields over time with N4 fertilization level. As addressed in the previous section, the N addition to soils from atmospheric deposition and N-fixation by crops such as groundnut and in paddy field (Shrestha and Maskey 2005) is supposed to be an important extra N fertilizer source in our modeling. This input, even small, will be particularly helpful to maintain and increase crop yields when N fertilizers' supply is limited or lack in the study area. Normally, both soil N availability and crop yield can mutually benefit. Because differences in demand of crop species for N nutrient, each crop will respond differently to the same level of N supply. For instance, groundnut does not require external N supply because of its N-fixation ability (Murata et al. 2002); reversely, external N application will inhibit the N-fixation and therefore lead to a reduction in yield (see Fig. 2d).

3.3 Variations of SOC stock and crop yields as related to climate stresses

The statistics presented in Table 7 indicate that the impacts of climate variables on SOC budgets vary with the nature of ecosystem and on crop yields vary with crop species. For the natural ecosystems (including open forest, savanna, and grass/herb in this study), any reduction in annual precipitation within the projected change regimes

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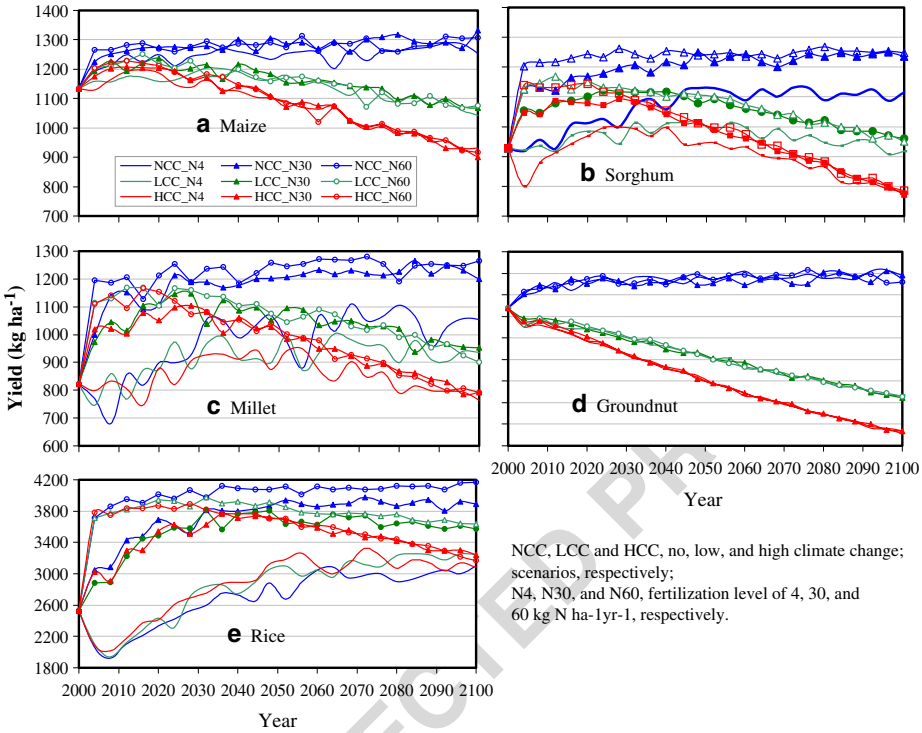

Fig. 2 Simulated responses of crop yields (in dry biomass) to nitrogen fertilization rates under climate change scenarios by 2100 in Bawku district (**b**–**e** have the same legend as **a**)

will significantly limit SOC accumulation despite the favorable effects of warming under LCC. For managed cropland, however, SOC stocks in all croplands are significantly negatively related to temperature and annual precipitation, particularly under HCC. In other words, warming will significantly enhance SOC emissions which could be weakened by the reduction in annual precipitation within the projected change regimes. This may imply that existing annual precipitation is enough for crop production requirement and some less annual precipitation may be favorable to optimize biomass production of these crops because they are usually suitable to grow well in semiarid areas. It is just the interaction of both warming and drying on SOC budgets that results in little change in SOC stock in all croplands over the twenty-first century under LCC and HCC (see Table 5). Generally, SOC stocks of all croplands will significantly depend on the changes in the precipitation during the growing season, in temperature, or in both, assuming no changes in land use and management will take place. An increase in temperature will accelerate SOC emissions from all croplands under both LCC and HCC even though the rate of SOC emissions could be significantly reduced under less precipitation within the projected climate change regimes. These climate variables explain 86% of the variance of SOC under HCC and 66% under LCC for croplands, while they constraint greater than 90% of the SOC estimate variance for all natural ecosystems, implying that some other factors should be also considered together to determine their partial contributions to SOC dynamics in croplands under a varying climate.

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Q3 **Table 7** Partial correlations of SOC stocks and crop yields to climate variables

Climate change scenario	Driving variable	Partial correlation coefficient									
		SOC stock				Crop yield					
		Forest	Savanna	Grass/herb	Cropland	Maize	Sorghum	Millet	Rice	Groundnut	Average
LCC	Annual precipitation	0.73***	0.72***	0.74***	−0.78***	0.22	0.05	−0.02	−0.22	0.31	−0.16
	Mean annual min temp	0.36*	0.35*	0.33	−0.32	−0.02	0.22	0.22	−0.09	−0.18	0.17
	Mean annual max temp	0.47**	0.44**	0.49**	−0.68***	−0.32	−0.17	−0.22	−0.12	0.22	−0.31
	Soil organic C content					0.62***	0.64***	0.35*	0.31	−0.00	0.37*
Statistics	% of variance explained	91	93	96	66	85	69	51	86	99	71
	F value	76	93	170	14	29	11	5.4	31	663	13
	Pr > F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.003	<0.001	<0.001	<0.001
HCC	Annual precipitation	0.85***	0.84***	0.89***	−0.93***	0.32	−0.47**	−0.14	−0.50**	0.42**	0.07
	Mean annual min temp	0.33	0.27	0.23	−0.44**	0.01	0.17	0.08	0.12	0.15	0.40*
	Mean annual max temp	0.23	0.24	0.39*	−0.49**	0.20	−0.39*	−0.22	−0.52**	−0.13	−0.29
	Soil organic C content					0.69***	0.40*	0.33	−0.08	−0.08	0.45**
Statistics	% of variance explained	96	97	98	86	97	94	64	90	100	68
	F value	174	218	445	44	156	82	9.4	49	1905	11
	Pr > F	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

LCC low climate change scenario, *HCC* high climate change scenario
$*a = 0.1$, $**a = 0.05$, $***a = 0.01$

Unlike SOC stock, crop yield appears to be less sensitive to the warming–drying stress, but it depends more on the soil fertility (in terms of SOC stock in the top 20-cm soil layer) (see Table 7). In other words, crops grown on soils with higher soil fertility are less impacted by climate change within the projected weather variable regimes. The grain yields of maize, sorghum, and millet significantly depend on soil fertility and much less on climate variables. Note that the response of rice to precipitation could be wrong because it was assumed to have enough water from irrigation in our model simulations. In fact more rainfall can help reduce irrigation loading. Compared to other crops, rice production has the greatest potential increase in grain yield with an increase in N fertilization and is least influenced by the warming–drying stress (see Table 7 and Fig. 2). In contrast, a significant reduction in groundnut yield may result from an increment in both N fertilization rate and progressive warming–drying stress. Note that groundnut growth can be independent of N fertilizers because groundnut has an N-fixation capacity through symbiotic relations with rhizobia and does not need an extra N supply during its growing period (Murata et al. 2002).

4 Conclusions

(1) Soil organic carbon dynamics in the study area over the twenty-first century in response to climate change are more sensitive in natural ecosystems than in cropping systems.
(2) In view of crop yields, soil fertility (usually SOC content is considered one of most important indicators) will be more critical than are climate variables.
(3) The responses of crop yields to precipitation are much less sensitive than to temperature and N fertilization rates in the study area because the mean annual precipitation in the study area is high enough for existing crop species' production because the projected annual precipitation is still as high as 750 mm even under HCC.
(4) A modest rate of fertilizer application (e.g., 30 kg N ha^{-1} $year^{-1}$) could lead to sustainable and productive cropping systems. A limited source of N fertilizers can be first allocated for rice (assuming irrigation is possible), then for millet and sorghum.
(5) Food security and agricultural sustainability in the savanna zone under potentially warming–drying climate will greatly rely on N fertilization rates.

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