Ecosystem carbon budgets and crop yields in response to changes in climate and nitrogen fertilization across an African savanna

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Introduction

The tropical savanna in West Africa is a critical ecosystem that provides goods and services for agriculturists, pastoralists, wildlife, and global climate. It is, however, sensitive to land disturbances and among the world's regions most vulnerable to climate change. The changes in land management and future climate will not only determine ecosystem carbon budgets but also substantially impact crop production and food security. We document the historical changes in ecosystem carbon and simulate the sensitivity of ecosystem carbon stocks to changes in land use/land cover, management, and projected progressive warming scenarios during the 21st century. This analysis of the savanna system completes the study of the major ecoregions of Ghana, a country with substantial historical carbon loss.

Methods

Study Area

The Bawku district belongs to a tropical savanna ecosystem in northern Ghana (fig. 1). The mean annual minimum and maximum temperature between 1972 and 2000 was 22.6°C and 31.9°C, respectively, and annual precipitation was 1,008 mm. Land cover during that period was dominated by the open cultivated savanna ecosystems, accounting for 79 percent of all land area. Major crop species include groundnut, sorghum, millet, and rice.

Figure 1. Bawku savanna zone in contrast to Ejura-Sekyedumasi forest-savanna transitional zone in the center and Assin forest zone in the south of Ghana.

Modeling System

The General Ensemble biogeochemical Modeling System (GEMS) (Liu et al., 2004) was used to simulate C dynamics in vegetation and soil. GEMS was developed for integrating well-established ecosystem models (e.g., CENTURY) with various spatial databases to provide simulations of biogeochemical cycles over large areas.

Climate Scenarios for the 21st Century (References: Ghana EPA, 2000; Hulme et al., 2001)

1. No Climate Change (NCC): average precipitation and mean monthly minimum and maximum temperature from 1972 to 2000 are used for the 21st century.
2. Low Climate Change (LCC): by the year 2100 the annual precipitation decreases by 105 mm and mean monthly minimum and maximum temperatures increase by 2.6°C and 3.1°C, respectively.
3. High Climate Change (HCC): by the year 2100 the annual precipitation decreases by 240 mm and mean monthly minimum and maximum temperatures increase by 3.8°C and 4.7°C, respectively.

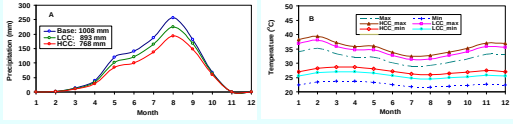

Figure 2. Differences in monthly precipitation and temperatures between climate change scenarios through the 21st century.

Nitrogen Fertilization Scenarios for the 21st Century

1. N04: the average nitrogen (N) fertilizer level of 4 kg N $ha^{-1}yr^{-1}$ continues
2. N3: the nitrogen fertilizer level increases to 30 kg N $ha^{-1}yr^{-1}$
3. N6: the nitrogen fertilizer level increases to 60 kg N $ha^{-1}yr^{-1}$

Results

Temporal and Spatial Variations in Carbon Stocks during the Past Century

At the ecoregion scale, the deforestation for farming cultivation has resulted in a reduction in ecosystem carbon stock from 136 Mg C ha^{-1} in 1900 to 36 Mg C ha^{-1} in 2000. Meanwhile, the SOC stock reduced from 32 to 20 Mg C ha^{-1} (fig. 3).

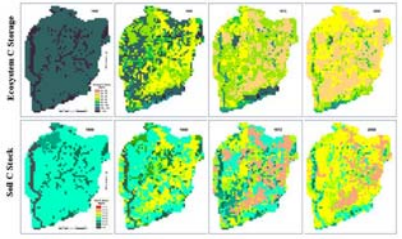

Figure 3. Temporal and spatial trends of ecosystem C and SOC stocks in the past century.

Change Trends of Carbon Stocks as Related to Climate Change Scenarios in the 21st Century

As illustrated in figure 4, if no change in land use/land cover, both ecosystem carbon and soil carbon stocks will decline with progressing warming through the 21st century, but the decrease rate will be greater under HCC than under LCC. In comparison to those under NCC at the ecoregion scale, HCC will lead to a reduction in ecosystem carbon and soil carbon stock by 19 percent and 7 percent, respectively, by 2100. However, such responses vary with land use/land cover type: the grass/herbaceous land shows the greatest reduction in both stocks (42 percent and 31 percent), and the cultivated savannas are to be least impacted.

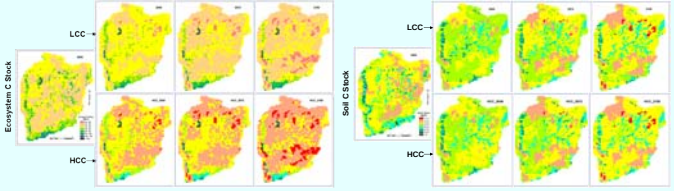

Figure 4. Simulated responses of ecosystem C and SOC stocks to both the low climate change (LCC) and the high climate change (HCC) scenarios in Bawku over the 21st century.

Dynamics of Carbon Stocks as Related to Nitrogen Fertilization

Figure 5-A shows that an increase in nitrogen fertilization will generally enhance soil carbon sequestration but stabilize slightly above 21 Mg C ha^{-1}. The extent will depend on how severe the warming becomes. The positive effects of nitrogen fertilization on soil carbon budget will eventually be offset by the warming-induced C emissions. A similar trend will happen to soil organic nitrogen stock (fig. 5-B).

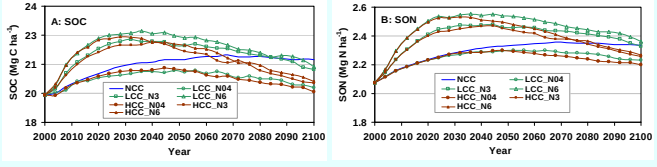

Figure 5. Responses of soil organic C (SOC) stocks in different cropping systems to N fertilization levels under climate change scenarios (NCC, no climate change with 4 kg N $ha^{-1}yr^{-1}$; LCC and HCC, low and high climate change scenarios, respectively; N04, N3, and N6, fertilization of 4, 30, and 60 kg N $ha^{-1}yr^{-1}$, respectively).

Effects of Nitrogen Fertilization on Crop Yields

As indicated by figure 6, responses of crop yields to nitrogen fertilization levels depend not only on the crop species but also on the climate change scenarios. The adverse impacts of a progressive warming on grain yields are noticeable despite the role of nitrogen fertilization in improving crop production (also see table 1). Results suggest that the priority of limited nitrogen fertilizer source can be given to rice production, and an expansion of millet production can be an alternative in line with potential climate warming for sustaining agriculture and food security in the 21st century.

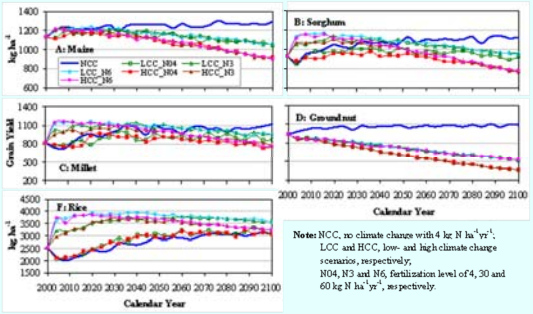

Figure 6. Simulated responses of crop yields (biomass rather than carbon only) to nitrogen fertilization under climate change scenarios by 2100 (abbreviations are the same as in fig. 5).

Table 1. Average grain yields of major crops and changes with N fertilization levels and climate change scenarios through the 21st century.

Crop	Area[a]	Base[b]	N_N4	N_N30	N_N60	L_N4	L_N30	L_N60	H_N4	H_N30	H_N60
	%	Mg $ha^{-1}yr^{-1}$									
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

[a] percentage of all planted area. [b] grain yield of dry biomass averaged from 1972 to 2000. [c] area-weight average.
N, no climate change; L, low climate change; H, high climate change.

Conclusions

1. Bawku ecoregion has experienced significant land degradation, especially both the grass/herb and the cultivated savanna in the past century. In the absence of changes in policy or management such degradation will likely continue through the 21st century under both high and low climate change scenarios.
2. An increase in N fertilization will enhance C sequestration into soil and vegetation, thereby facilitating a sustainable agriculture. The effects of N fertilization on crop yields depend on the crop species. Priority of N fertilization should be considered for millet production, although rice, with adequate irrigation, also maintains high response to N.
3. These results should be useful for policy makers and farm managers as they evaluate mitigation and adaptation strategies of cropping systems and management practices to sustain land resources and farming production under a changing climate.
4. Despite the general trend of C dynamics similar to those in Assin and Ejura, the Bawku savanna ecosystem shows the most sensitivity to the projected progressive warming climate because of its lowest baseline precipitation and highest baseline minimum temperature in comparison to other two ecoregions.

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