Environmental Monitoring and Information Systems (EMIS)
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Theme 4 – Sustainable Tree Crop Management, Monitoring, and Certification
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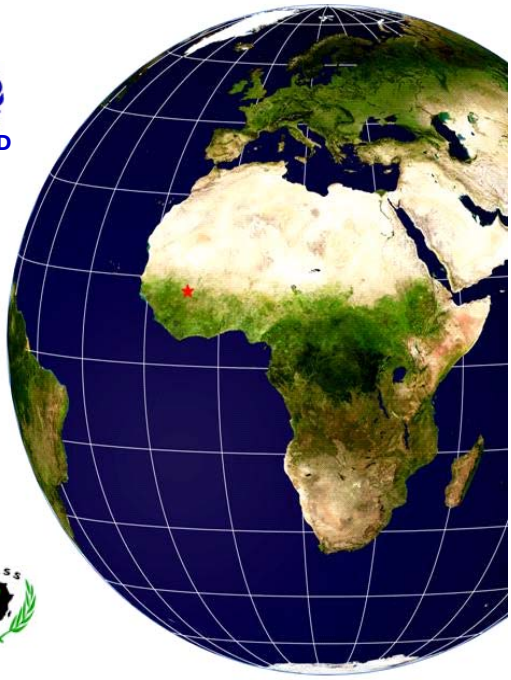
SEMSOC
LULUC and Carbon West Africa



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Land Cover Change, Biogeochemical Modeling of Carbon Stocks, and Climate Change in West Africa

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Abstract

The carbon in ecosystems exists in dynamic soil and vegetation pools which vary in amounts and cycle with the global atmosphere at varying rates. These stocks and fluxes play important roles in global carbon regulation and in the maintenance of goods and services. Changes in land cover or ecosystems result in increased or decreased fluxes to the atmosphere and play a major role in climate regulation. Carbon in soil is closely coupled to soil nitrogen, and the continued mining of soil for crops or fuel without replenishment of nutrients results in decreased productivity and impacts food security. The assessment of these processes across large areas, although difficult, is aided by the integration of simulation modeling (biogeochemical and ecosystem) and remote sensing.
We acquired satellite imagery for four periods from the 1960s to 2000s, trained environmental scientists from 14 countries on image analysis and interpretation, and now report systematic analyses of land cover changes in select countries of West Africa and quantify potential impacts of climate change and management at specific sites. Statistical changes and maps of land cover are documented for most countries. Senegal, for example, illustrates a 57 percent loss in dense forests between 1975 and 2000 with an even greater loss rate in the preceding 10 years. Bare soil increased 16.6 percent, often related to unproductive "badland" formation. Settlements increased 45.6 percent, and reforestation replaced bare sandy areas for sand dune stabilization. In some countries (Senegal and Ghana), the impact of these conversions and changes in land management and future projections has been incorporated into biogeochemical models to quantify carbon changes and project future carbon and crop scenarios. We present current assessments of carbon fluxes and the availability of data for these West African countries.

Keywords: West Africa, Carbon fluxes, Land cover change, Sequestration, Climate change, Biogeochemical modeling, Agricultural management

Introduction

Climate change during this century has the potential to modify existing ecosystem (including intensively managed systems, e.g., agricultural and pastoral) functions in diverse ways, including both the enhancement and reduction of crop yields and production. These impacts are potentially profound in the areas of the world that are most vulnerable – those that experience the threat of climate change and have limited abilities to adapt. Sub-Saharan Africa contains

some of these vulnerable systems (Vagen *et al*. 2005, and Tieszen *et al*. 2004). Recent analyses (Battisti and Naylor 2009) confirm the potentially harmful impact suggested by climate change scenarios, especially those associated with increasing temperature. This was suggested by the simulations conducted in Senegal (Liu *et al.* 2004), which projected crop failure for existing genetic types.

In addition to this vulnerability, the continent plays a major role in the global carbon cycle at scales ranging from seasonal to decadal, even though our understanding of this is severely limited (Williams *et al*. 2007). Africa's major role in the global carbon cycle can be attributed to the substantial releases of carbon associated with land use conversions from forest or woodlands to agriculture (Smith 2008), which accounted for approximately 15 percent of the global net flux of carbon from just land use changes in the 1990s (Houghton and Hackler 2006). Land management following conversion also impacts carbon status, soil fertility, and agricultural sustainability as repeatedly suggested by Lal (2006), Ringius (2002), and others (Graff-Zivin and Lipper 2008; Tieszen *et al*. 2004). Soils often continue to lose carbon following land conversion (Woomer *et al*. 2004; Tschakert *et al*. 2004; Liu *et al*. 2004), resulting in further reductions in crop yields and continued impoverishment; however, these carbon stocks can be replenished with combinations of residue retention, manuring, N fertilization, agroforestry, and conservation practices (Lal 2006). This understanding has led to continuing suggestions of the importance of soil carbon sequestration and the Clean Development Mechanism (CDM) of the Kyoto Protocol.

This publication describes the results of two development projects undertaken in West Africa. The West Africa Land Cover/Land Use project built capacity with teams in each country to use remote sensing and ground validation to document current land cover and recent changes. The Environmental Management and Information Systems project quantified carbon changes with Spatially Explicit Modeling of Soil Organic Carbon (SEMSOC). We summarize our quantification of changes in land cover types in West Africa, evaluate associated changes in ecosystem and soil carbon stocks in selected study areas of Ghana and Senegal, and simulate changes in carbon status under selected management and projected changing climate during the twenty-first century.

Materials and methods

Since 1972, earth resource observation satellites from the Landsat series have furnished numerous time-series images of Africa. These images made it feasible to map and quantify land use and land cover (LULC) changes over time. These historical and recent satellite images allowed us to spatially document changes in the natural resources, many of which are driven by human activity. We mapped and assessed trends in LULC across 12 West African countries based on two time periods of imagery: Landsat multispectral scanner (MSS) images with a nominal date of 1975 (using images from 1972 to 1978) and Landsat enhanced thematic mapper (ETM+) images with a nominal date of 2000 (using images from 1999 to 2001). We defined 18 general LULC classes that could be readily identified on Landsat imagery. LULC trends statistics for Mali and Chad are not yet available.

A manual photo-interpretation approach was used to identify and map the LULC classes because it accommodates images from different satellite systems and formats, it allows expert interpreters to integrate local knowledge with the many dimensions of information contained in images, and it resolves some problems of seasonality, differences in illumination, and atmospheric effects. Furthermore, the human interpreter can effectively distinguish real LULC changes from many of the ephemeral factors such as annual grass fires. The interpretation was verified where possible with field visits, high resolution commercial satellite imagery, and by reviewing thousands of aerial photographs. This led to very high interpretation accuracy and consistency.

We developed a new approach to map LULC efficiently over 12 participating countries and several periods in time. This tool, the Rapid Land Cover Mapper (RLCM), is a vector–raster hybrid approach that lends itself to time-series LULC mapping. The tool overlays a dot grid on an image within ESRI's ArcMap GIS software, and the analyst identifies the discrete LULC class for each dot. The RLCM tool facilitates both the selection and attribution of dots within a common LULC class. It also facilitates the management of multiple time period classifications for the study area. Once the dot grid matrix is completely classified for a given time period, a raster LULC map can be generated. The same process can be applied to different time periods, and the resulting maps can be compared to assess change over time. We produced 2 km resolution raster LULC maps for the nominal time periods of 1975 and 2000 (Figure 1) and derived both trends and change maps.

We used the General Ensemble biogeochemical Modeling System (GEMS, refer to Liu *et al*. 2004; Tan *et al*. 2009b for details) to simulate historical changes in ecosystem and soil carbon stocks in the twentieth century and predicted their dynamic trends under projected climate change scenarios in the twenty-first century for three ecoregions of Ghana (Figure 2). The input geospatial data consisted of mean monthly precipitation, mean monthly minimum and maximum temperatures from 1971 to 2000, three interpreted images from 1972, 1986, and 2000, and the FAO soil database. Management practices (crop composition, crop rotation, fallow, tillage, harvesting options, frequency of fuelwood production, etc.) were synthesized from field observations across all studied areas and literature. GEMS automates the processes of downscaling those data for carbon budget simulations. The field data of ecosystem and soil carbon stocks collected by Ghana EPA in 2006 from three districts of Bawku, Ejura, and Assin of Ghana) and the grain yields of major crops were used as references to verify modeling outputs. The details in GEMS architecture and ensemble simulations and the scenarios of climate change and nitrogen fertilization rates for model simulations are published (Liu *et al*. 2004; Tan *et al*. 2009a, 2009b).

Results and discussion

Research teams were trained in image interpretation, including the use of the RLCM (http://edcintl.cr.usgs.gov/ip_dev/new/rlcm/index.php), and were provided imagery for 1975, ca. 1985, and ca. 2000. Initial land cover analyses with Landsat imagery was aided with high resolution imagery and ground validated at some specific sites. These national maps and change products are now available (http://edcintl.cr.usgs.gov/ip_dev/new/africalulc/index.php) and will only be summarized here. Figure 1 represents the land cover for the area of West

Africa completed with year 2000 imagery. Details of each country are available including assessments of major drivers of land cover change. Table 1 summarizes the results for six countries in West Africa revealing similar patterns in land cover change during the period 1975–2000. All countries lost forest cover ranging from around 8 percent loss in Senegal to slightly over 30 percent in Niger. Similar losses characterized the savannah classes in all countries. These changes were accompanied by substantial increases in the agricultural classes approaching 90 percent increases in Ghana and Togo. Although Senegal revealed a very small increase in agriculture land cover, closer inspection reveals the necessity for close and detailed inspections of these country level statistics. In Senegal, although there was only a small increase in agricultural land, there was a substantial loss of this class in the "old peanut basin" as these lands were abandoned but a substantial conversion to agriculture in other ecoregions. Thus the summarized statistics mask a change in land cover that has potentially large impacts on carbon budgets for the country.

Earlier research (Woomer *et al*. 2004) summarized countrywide estimates of carbon status in Senegal and estimated the changes in carbon stocks between 1965 and 2000. These estimates showed that seven of the eight zones (aggregated ecoregions) lost substantial carbon and that the terrestrial losses for the country were 293 Mt during this period, an average of 418 kg C $ha^{-1}year^{-1}$. Only one area, "Northern Coast," showed increasing carbon stocks, an increase accounted for by afforestation associated with long-term projects to introduce forest species for dune stabilization. Furthermore, this study showed that 95 percent of the carbon loss resulted from land cover conversion or decreases in woody cover (thinning, for example). Extensive simulation modeling over two areas in Senegal revealed continuing soil carbon losses from agriculture, mostly caused by residue removal and lack of nitrogen inputs (Tschakert *et al*. 2004; Liu *et al*. 2004). Opportunities for soil carbon restoration were defined; however, most of them were not economically viable under existing conditions without increased commodity prices, credit for fertilizer, or the sale of carbon credits. Simulations also suggested continued soil carbon deterioration under climate change scenarios and even crop failures resulting from higher temperatures and greater evapotranspiration. Interestingly, this response to increasing temperature was highlighted recently by Battisti and Naylor (2009).

In addition to the summary land cover data for Ghana presented above, the details of land cover change and carbon cycling have been studied in three ecoregions (Figure 2) encompassing the terrestrial range across Ghana (Tan *et al*. 2009a, 2009b, 2009c). Bawku, in the semi-arid region, lost woody savannah and gallery forest mainly to agricultural use (Table 2). Similar conversions of forest to agriculture occurred in Ejura and Assin. Table 3 summarizes the changes in ecosystem and soil carbon stocks from 1900 to 2000 in each intensively studied area. The combination of land cover change and management resulted in losses of ecosystem carbon approaching 50 percent in each area. This amounted to an average loss of 153 Mg ha^{-1} (294, 168, and 76 Mg ha^{-1} from closed forest, degradaed forest and cropland, respectively) in the humid forest area of Assin. Simulations of three climate change scenarios show losses of both ecosystem carbon and soil carbon by 2100. Interestingly, soil carbon was not depleted in the semi-arid Bawku region but declined sharply in humid Assin, probably a legacy of the larger carbon stores from forest-derived soils. Because nutrient replacement is essential to maintain soil carbon, we simulated the responses to climate change under three levels of nitrogen fertilization. The addition of nitrogen fertilizer at rates of 30 and

60 kg N $ha^{-1}yr^{-1}$ actually stimulated carbon sequestration in soils at all sites. Even this stimulation, however, was overridden by both low and high climate change scenarios around 2050. Crop yields declined slightly with climate change but were stimulated under all climate change scenarios with nitrogen fertilization.

Conclusions

Remote sensing has allowed the documentation of land cover changes across West Africa and offers the opportunity for continued assessments with the availability (http://landsat.usgs.gov/science_GLS2005.php)of Global Land Survey 2005 data at no cost. These analyses have shown substantial conversions of land cover from forests (deforestation) and woodlands to agricultural uses in all countries. These changes have resulted in substantial releases of carbon from these systems to the atmosphere, and land uses for agriculture in the absence of fertilizer inputs and residue retention have continued to degrade soils as both carbon and nitrogen have been mined. Simulations of the biogeochemical conversions and fluxes under various management and climate scenarios show dramatically that the "business as usual" land use and management scenarios will result in continued carbon losses and reduced crop sustainability, thereby threatening food security. Furthermore, the simulations of suggested climate change scenarios suggest that the increased temperatures will threaten traditional crop species and reduce yields in the hotter parts of West Africa.

Opportunities for adaptation, and even mitigation, do exist and can be implemented. Soil carbon can be restored with improved conservation practices, appropriate residue management and increased nitrogen input, either from inorganic sources or biological fixation, even as temperatures in West Africa increase with climate change. This restoration has the potential to improve food security, restore depleted soil carbon, reduce expanded deforestation, and improve the livelihoods of subsistence farmers. These benefits can be secured with greater attention to the importance of soil carbon for both mitigation and adaptation for climate change. Therefore, these results proclaim the importance of carbon crediting for ***Soil Carbon Uptake for Restoration and Sustainability (SCURS),*** our proposed analogue to Reduced Emissions from Deforestation and Degradation (REDD).

Acknowledgements:

This is a contribution of SEMSOC (AEGP00030001300), funded by the US Agency for International Development (USAID)/Climate Change program, Bureaus for Economic Growth, Agriculture, and Trade (EGAT) and Africa Bureau. Research was supported and integrated with the Geographic Analysis and Monitoring (GAM) and the Earth Surface Dynamics programs of the U.S. Geological Survey. The authors thank Zhengpeng Li for assistance in model implementation.

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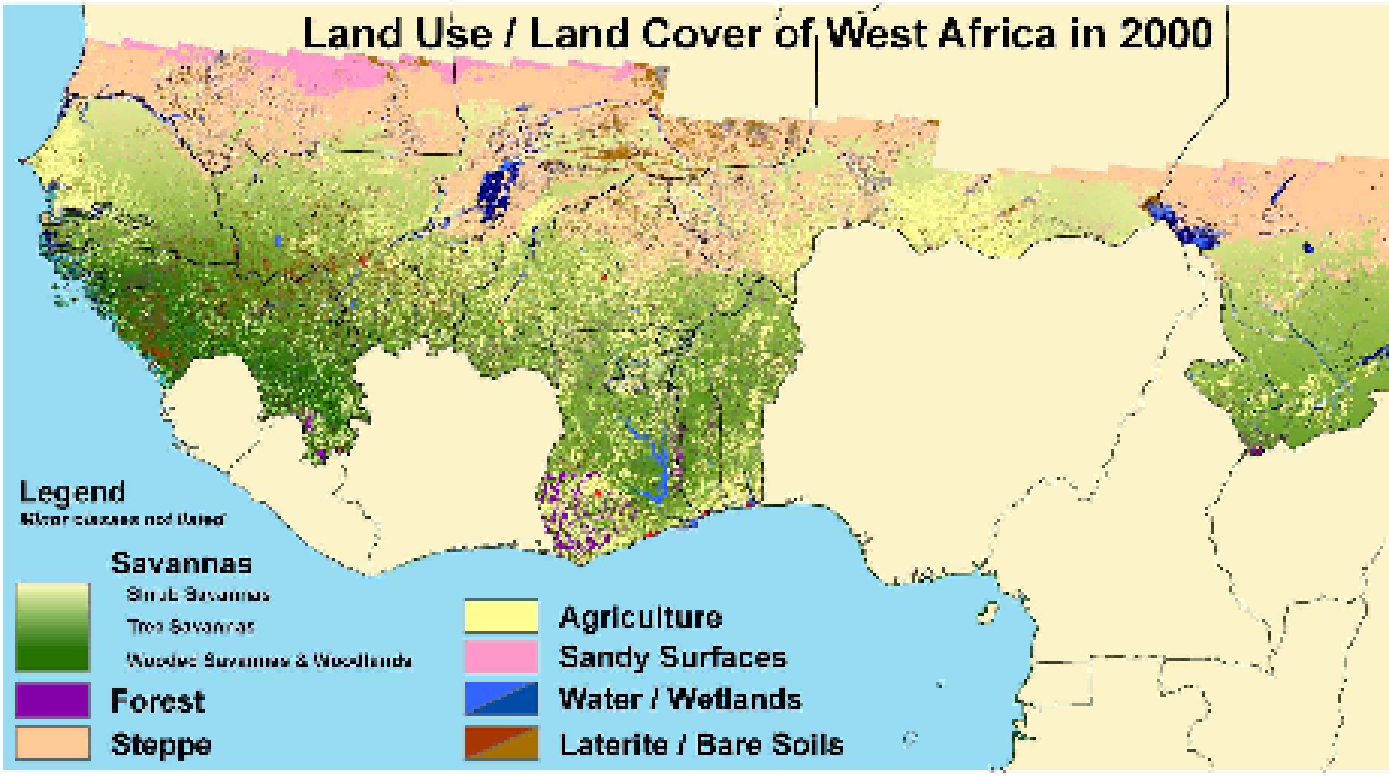
Figure 1.


Land Use / Land Cover of West Africa in 2000
Legend
Savannas
Forest
Steppe
Agriculture
Sandy Surfaces
Water / Wetlands
Laterite / Bare Soils

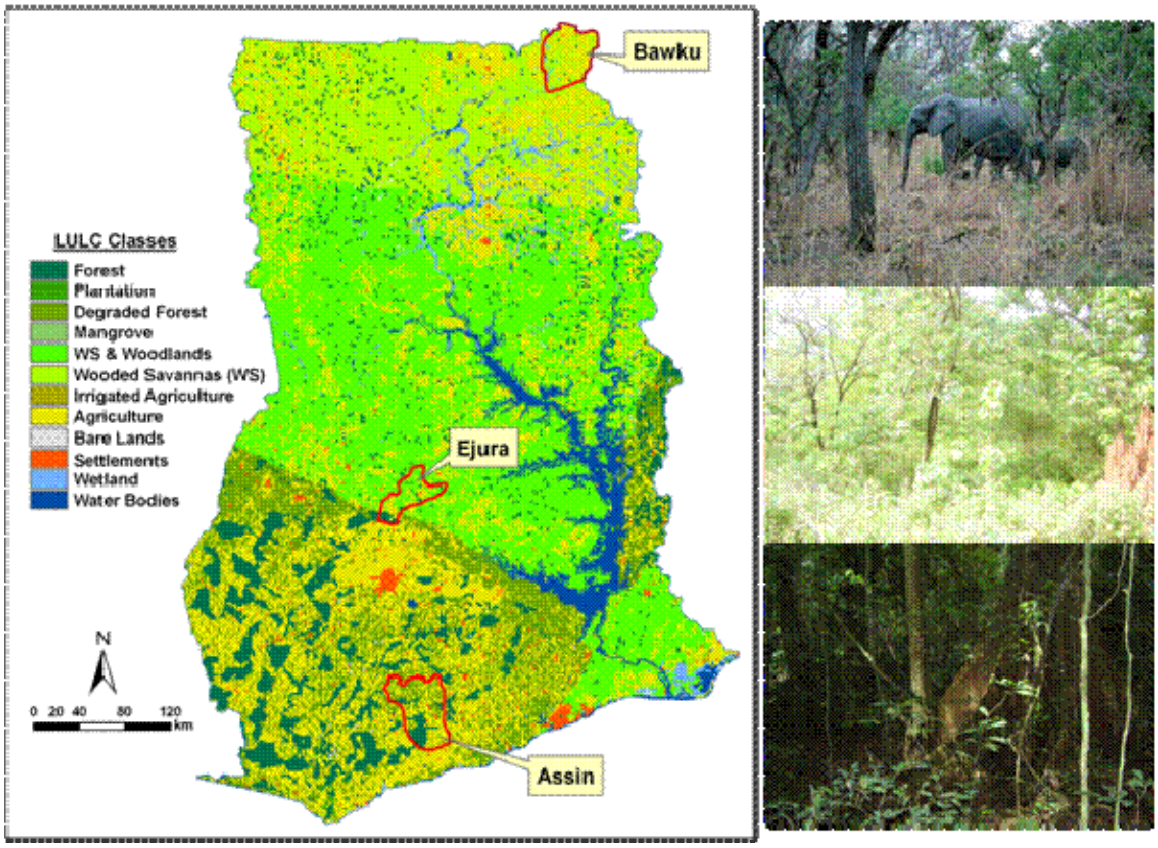


Figure 2. Locations of three study areas in Ghana: the Bawku District, the Ejura-Sekyedumasi District, and the Assin District as indicated on the left image, and their typical landscapes (photos on the right), respectively. The land use and land cover (LULC) classes for the whole Ghana were derived from Landsat imagery of 2000.

Table 1. Summary of the percent changes in major land use/land cover classes for six West African countries during the period 1975 to 2000. Note the major declines in forest and savanna classes, and the significant increase in agriculture.

	Ghana	Senegal	Guinea	Niger	Benin	Togo
Forest	-18	-60.6	-29.9		27.1	-34
Gallery Forest	-10.9	-1.6	-10.2	-30.9	-8.8	-5.1
Total Forest	-16.4	-7.9	-19.5	-30.9	-12	-20.8
Steppe	0	4.9	0	-3.4	0	0
Savannas	-15.7	-1.1	-2.5	-16.2	-13	-12.8
Wetland - Floodplain	4.1	10.3	7.2	-13.7	6.3	7.9
Water Bodies	-8.9	8	39.5	9.1	5.7	17.6
Plantation	41.7	10.3	0	0	125	650
Mangrove	0	-4	-0.2	0	0	0
Agriculture	96	0.4	29.4	42.7	77.7	80.1
Irrigated Agriculture	325	102.4	0	27.3	9.1	233.3
Total Agriculture	96.2	1.4	29.3	42.5	77.1	80.9
Sandy surfaces	0	-70.9	0	71.5	-100	0
Bare Soil	104.8	0	80	54.9	53.3	333.3
Settlements	48.9	44.1	34.3	26.9	45.2	70

Table 2. Areal change (%) of major land use and land cover classes by 2000 from 1975 detected within three ecoregions in Ghana.

District	Forest	Gallery Forest	Agriculture	Wooded savannas and woodlands	Wooded savannas	Degraded Forest	Wetlands	Settlements
Bawku		-56	41		-27		27	
Ejura	-8		159	-23		-62		
Assin	-22		53			-23		40

Table 3. Ecosystem and soil carbon changes associated with projected climate scenarios for three ecoregions in Ghana.

District	Carbon stock	1900	2000	Change[a]	NCC		LCC		HCC	
					2100	Change[b]	2100	Change[b]	2100	Change[b]
		Mg ha^{-1}		%	Mg ha^{-1}	%	Mg ha^{-1}	%	Mg ha^{-1}	%
Bawku	Ecosystem	131	36	-73	31	-12	30	-17	29	-19
	Soil	32	20	-38	20	1	19	-5	18	-7
Ejura	Ecosystem	135	77	-43	74	-4	73	-5	71	-8
	Soil	27	21	-20	20	-6	18	-16	17	-20
Assin	Ecosystem	306	153	-50	146	-5	145	-5	143	-6
	Soil	53	44	-17	40	-10	38	-14	38	-15

[a] Percentage change in carbon stock by 2000 from 1900. [b] Percentage change in carbon stock by 2100 from 2000

NCC, LCC, and HCC represent no, low, and high climate change scenarios, respectively.

This table was synthesized from Tan et al., 2009a, 2009b, and 2009c.