LAND USE AND CLIMATE CHANGE EFFECTS ON TERRESTRIAL C STOCKS IN UGANDA'S CATTLE CORRIDOR

END OF PROJECT TECHNICAL REPORT SUBMITTED TO START

By Abel Lufafa

FACULTY OF AGRICULTURE, MAKERERE UNIVERSITY

October, 2006

Table of Contents

Acknowledgement

Many people contributed directly and indirectly to the accomplishment of this project. We thank the Soil and Water Conservation Society of Uganda for the collaborative effort and accepting to share with us most of their facilities at subsidized cost. We thank Dr. John Tenywa for his invaluable assistance with the laboratory analyses, the soil science technicians at Makerere University for working over time just to get us the results we so badly needed on time.

Finally, we thank the US National Science Foundation for funding this project through the START program and the Dean Faculty of Agriculture for managing the grant.

1.0 Introduction

The increasing concentration of CO2 in the atmosphere will impinge on stability of the Earth's climate system, human health, and long-term sustainability of socioeconomic systems (IPCC, 2001). Dynamics of carbon (C) in terrestrial ecosystems are a major factor regulating atmospheric CO2 concentration (Houghton, 1999; IPCC, 2001). In Uganda as well as in other African countries, there is a paucity of reliable field measurements of C stocks residing in important and representative ecological zones and how changes in land use and land cover in these zones impact on C stocks and consequently global climate change. Given the demands for national research organizations to support pressing developmental agendas and the fairly recent emergence of carbon studies within the global change agenda, this lack of information is understandable.

The Cattle Corridor - one of the two most fragile ecological zones in Uganda (NEMA, 2001) controls significant proportions of terrestrial C stocks and fluxes between the land-atmosphere interface in Uganda. The corridor straddles an area of 84,000 sq km (UNEP, 1999), is characterized by a semiarid climate, vegetation cover that ranges from grasses interspersed with trees, to forest savannah mosaics and woodland in some areas, and a high susceptibility to changes in land use (NEMA, 2001). The corridor has come to be synonymous to desertification in Uganda and anecdotal evidence indicates that this region experienced large-scale land clearing and conversion in the past several decades and currently, it is estimated that 9% of this area is lost annually to land clearing. Most of the cleared land is used for grazing, and with close to 70% of the livestock in Uganda in this area, there is evidence of overstocking and overgrazing.

A significant body of research links land use and land cover change with changes in terrestrial C stocks. Overgrazing and its effects; particularly soil erosion and soil compaction have been documented to cause negative changes in C stocks.

What are the C stocks in the Cattle Corridor and how has overgrazing and changes in land use impacted these stocks?

Under its 2006 call for proposals, START funded work geared towards:

- characterizing and quantifying historical land use and land use changes in the Cattle Corridor;
- cataloging contemporary C stocks in vegetation and soils of the corridor and assessing soil C fluxes following land clearing;
- estimating historical and projecting future changes in Cattle Corridor total carbon levels owing to land use and potential climate changes.

This report is summary of the work done under the project.

2.0 Approach

The approach used in this project was: 1) to procure software and imagery 2) to characterize land use change, 3) to estimate carbon stocks and 4) simulate regional carbon dynamics. This report is an account of the progress registered for each of the tasks.

2.1 Procurement

We procured 3 types of software i.e. i-Century, ENVI and ArcGIS. i-Century was obtained from Iowa State University at no cost and it is the domain for modeling carbon dynamics in the study area. Initially, we had not planned to purchase ArcGIS hoping to use a set that was already available at the Faculty. However the Faculty ArcGIS license was not renewed so we had to secure ArcGIS because it was needed to accomplish the work. Originally, we had anticipated that ENVI would cost $2000 but there was a price increase due to incorporation of an IDL license. We also procured various sets of Satellite images for use in land use change characterization and climate surfaces that are to be used in modeling/simulation of Carbon dynamics. Constraints encountered during the procurement included price increases relative to the approved budget and institutional bureaucratic delays. For example, In Uganda we have only one provider of Remote Sensing/GIS related software, data and services yet the University insisted that we provide at least three invoices for each purchase from which the procurement committee would chose the appropriate supplier. This took a lot of time to over come.

2.2 Land use change characterization

Land use change characterization was done using the procured satellite images. We tried to procure images from about the same time of year so the classification would be performed on the same basis but considerations of phenology and return times of Landsat MSS (18 days) and Landsat TM/ETM (16 days) made this a futile attempt. Consequently, we used the satellite images whose details are shown in Table 1.

Table 1. Overview of Landsat images used in the study area. The accuracy is given for a rectification with a second order polynomial

Sensor	Date	Resolution (m)	Accuracy
Landsat MSS	Dec, 1972	80 x 80	0.89
Landsat TM	Nov,1979	30 x 30	0.87
Landsat TM	Dec, 1981	30 x 30	1.05
Landsat ETM+	Oct, 1988	30 x 30	1.32
Landsat ETM+	Nov, 1990	30 x 30	1.03
Landsat ETM+	Nov, 1994	30 x 30	0.97
Landsat ETM+	Dec, 1998	30 x 30	0.91
Landsat ETM+	Nov, 2001	30 x 30	0.75
Landsat ETM+	Oct, 2002	30 x 30	0.56

It would have been possible to use images from more than 6 years but to reduce database complexity and size, only six were used and these were chosen so that they are distributed evenly over the possible 30 year period. The images are all from late or just after the rainy season as other images from the rainy season were too cloudy.

A supervised classification using ground truth data (training areas) was performed on the images but it yielded poor results. An unsupervised ISODATA classification was attempted but it also did not improve the results. For both supervised and unsupervised classification the problem was the separability between classes. After harvest of the fields and withering of the savanna, the fields are covered with residues from crops and the savanna with residues from grasses and the two classes do not have distinguishable spectral signatures. The Jeffies-Matusita distance between the two classes is 0.501 as opposed to requisite 1.41 that is needed to be able to separate the classes.

On the contrary, the structural characteristics of the fields are easily distinguished visually from the surrounding savanna. Consequently, the fastest and most efficient solution ended up being digitalizing the visually separable classes i.e. agricultural areas, plantations and savanna. The land use maps produced are shown below.

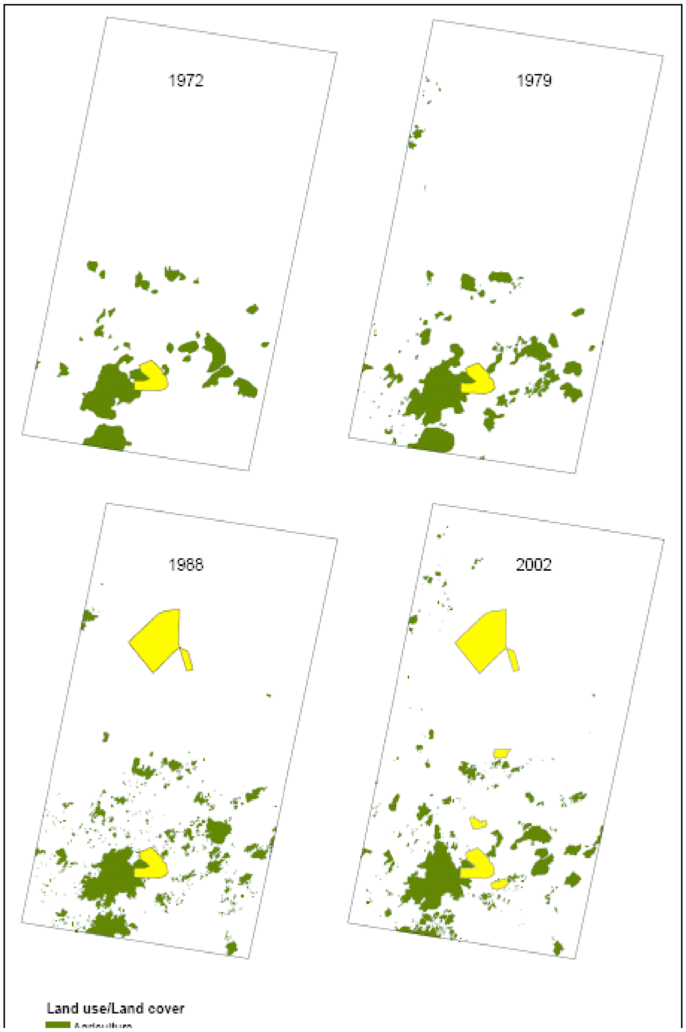

Figure 1.Land use maps digitalized from Landsat images, 1972, 1979, 1988 and 2002.

2.3 Carbon stock estimates and fluxes

A paired site sampling approach was used to quantify C stock changes following land clearing. P paired sites were stratified on the basis of vegetation type, soil type, and time since land clearing. Soils from the following microclimatic zones (Mountain areas, semi arid low lying zone, moist agricultural savanna and Middle range zone) were sampled. The two individual plots making up a paired site (uncleared and cleared), were carefully matched in terms of site factors (i.e. proximity, landscape position, slope, aspect, soil properties). Soil characterisation (profile description and laboratory analysis) for each plot was used to establish the validity of selected cleared and uncleared pairs. The corners and central positions of each plot were referenced using a Trimble differential global–positioning system.

Table 2 lists the sampled sites and relevant information for each. Of the 20 sites reported in this study, 8 have been used for crop production (mainly cereal production), while the remainder have been used for the grazing of low quality native pastures.

Table 2. List of the Cattle corridor paired C sites.

Region	Site Code	Year[1] Cleared	Land use after clearing
Mountain areas	START1	1978	Cropping
	START2	1988	Cropping
	START3	1993	Grazing
	START4	1998	Cropping
	START5	2000	Grazing
Semi arid low lying zone	START6	1980	Grazing
	START7	1985	Cropping
	START8	1991	Grazing
	START9	1999	Grazing
	START10	2002	Cropping
Moist agricultural savanna	START11	1976	Grazing
	START12	1984	Cropping
	START13	1996	Grazing
	START14	1999	Grazing
	START15	2001	Cropping
Middle range zone	START16	1979	Grazing
	START17	1985	Grazing
	START18	1990	Grazing
	START19	1994	Grazing
	START20	2002	Cropping

The sampling of soil, plant litter and coarse woody debris was based on the procedures outlined by McKenzie *et al.* (2000). The dimensions of sample plots varied, but they were always at least 0.1 ha in area. Five replicate soil samples were taken from each plot.

---

[1] Year of clearing was obtained from oral interviews, comparison with satellite images and anecdotal evidence

Soil was sampled to 1 m depth using an auger. Soil cores were sectioned into 0–0.05 m, 0.05–0.10 m, and then each 0.10 m depth interval. For the 0–0.30 m depth range, five samples from each depth increment were mixed to obtain one composite sample. Below 0.30 m, three samples were collected to obtain the composite sample. Bulk density was calculated from the composite cores. From each plot, an additional soil sample was taken for laboratory analysis.

Surface litter was measured using two 0.25 m^2 quadrats that were randomly placed along each soil sampling line. All the surface litter in the quadrat was collected and the percentage litter cover for each quadrat noted. Representative samples of coarse woody debris encountered in plots were collected and later used for calculating wood density.

Soil moisture content was determined by drying a sub–sample at $105^{o}C$ for 48 hrs. Bulk density was calculated from the oven–dried soil mass and the recorded field volume of soil. The remainder of the soil sample was air–dried ($40^{o}C$), and ground to pass through a 0.25 mm sieve used to determine total C. The mass and/or volume of separated coarse fragments (i.e. those that could not be ground), fine roots (<25 mm) and coarse charcoal were recorded. Total carbon[2] was determined using a high frequency induction furnace and infra–red detection (LECO CR12 analyser) for composite soil samples from the following depth increments: 0–0.05 m, 0.05–0.10 m, 0.10–0.20 m, 0.20–0.30 m, 0.30–0.60 m, and 0.60–1.00 m. Representative samples of fine roots, coarse charcoal, surface litter and coarse woody debris were also analysed for carbon using the same method. Surface litter samples were dried at $65^{o}C$ for 48 hours. Representative samples were separated into leaf material and woody material, ground and analysed in a LECO CR12 analyser for carbon

Mean site-soil carbon density, CD_{tot} (t/ha) for each site was obtained by summing all its components:

$CD_{tot} = CD_{CWD} + CD_{SL} + CD_{S} + CD_{SR} + CD_{SC}$.

Where CD_{CWD}, CD_{SL}, CD_{S}, CD_{SR}, and CD_{SC} are the carbon densities for coarse woody debris (CWD), surface litter (SL), soil (S), separated roots (SR) and separated charcoal (SC). For interpretation and analysis, sites were grouped according to major land use type (uncleared, grazing or cropping)

Results in Table 3 are for cumulative soil depths of 0.10, 0.30, 0.60 and 1.00 m and they incorporate values for litter and coarse woody debris as outlined in the CD^{tot} estimation equation.

---

[2] All carbon results quoted in this report therefore refer to total organic carbon and specifically exclude non–biological carbonate sources

Table 3. Mean site carbon density for all paired sites, and average change in carbon following land clearing.

Depth (m)	CD_{tot} (t/ha)		ΔCD_{tot}	
	Uncleared	Cleared	t/ha	% age
Grazing sites (n=12)				
0-0.10	21.16	15.88	5.27	24.93
0-0.30	40.34	31.41	8.93	22.14
0-0.60	56.87	45.65	11.22	19.73
0-1.00	71.61	59.25	12.36	17.26
Cropping sites (n=8)				
0-0.10	24.57	10.13	14.44	58.77
0-0.30	43.56	24.50	19.06	43.75
0-0.60	62.32	41.66	20.66	33.16
0-1.00	82.57	60.71	21.86	26.47

Despite an overall pattern of decline, trends in soil organic carbon change as a result of land clearing were variable, especially in land developed for grazing. Soils cleared for grazing lost much smaller amounts of organic carbon than the cropping soils. The average difference between soil carbon densities of uncleared and cleared sites was an imputed loss of 19 t/ha for cropped soils and 9.45 t/ha for grazing soils (to a depth of 1 m and including litter, plant roots and coarse charcoal). The corresponding losses in percentage terms were 40.5% for cropping and 21% for grazing soils. For sites that lost soil carbon, almost all the loss occurred in the 0–0.30 m depth range.

The magnitude of soil carbon decline in cropping soils is comparable to other studies reported in the literature. Russell and Williams (1982) found that decreases in organic carbon from cropping soils ranged from 10% to 60% over 10–80 years of cultivation. Haas *et al.* (1957) observed a similar range in organic carbon decline due to cultivation over similar periods in North American soils. The large variability between sites cleared for grazing is also consistent with other reported studies. Howden *et al*. (1995) found that surface organic carbon concentration increased on some grazing sites while on others it remained the same or decreased slightly. Similarly, Neill and Davidson (2000) found that conversion of forest soils to pastures in Brazil resulted in a decrease in organic carbon stocks in some soils while in other soils there was an increase or no effect on soil carbon levels.

2.4 Simulation of regional C dynamics

The conceptualization in Figure 2 below was conceived for simulating regional C dynamics in the study area.

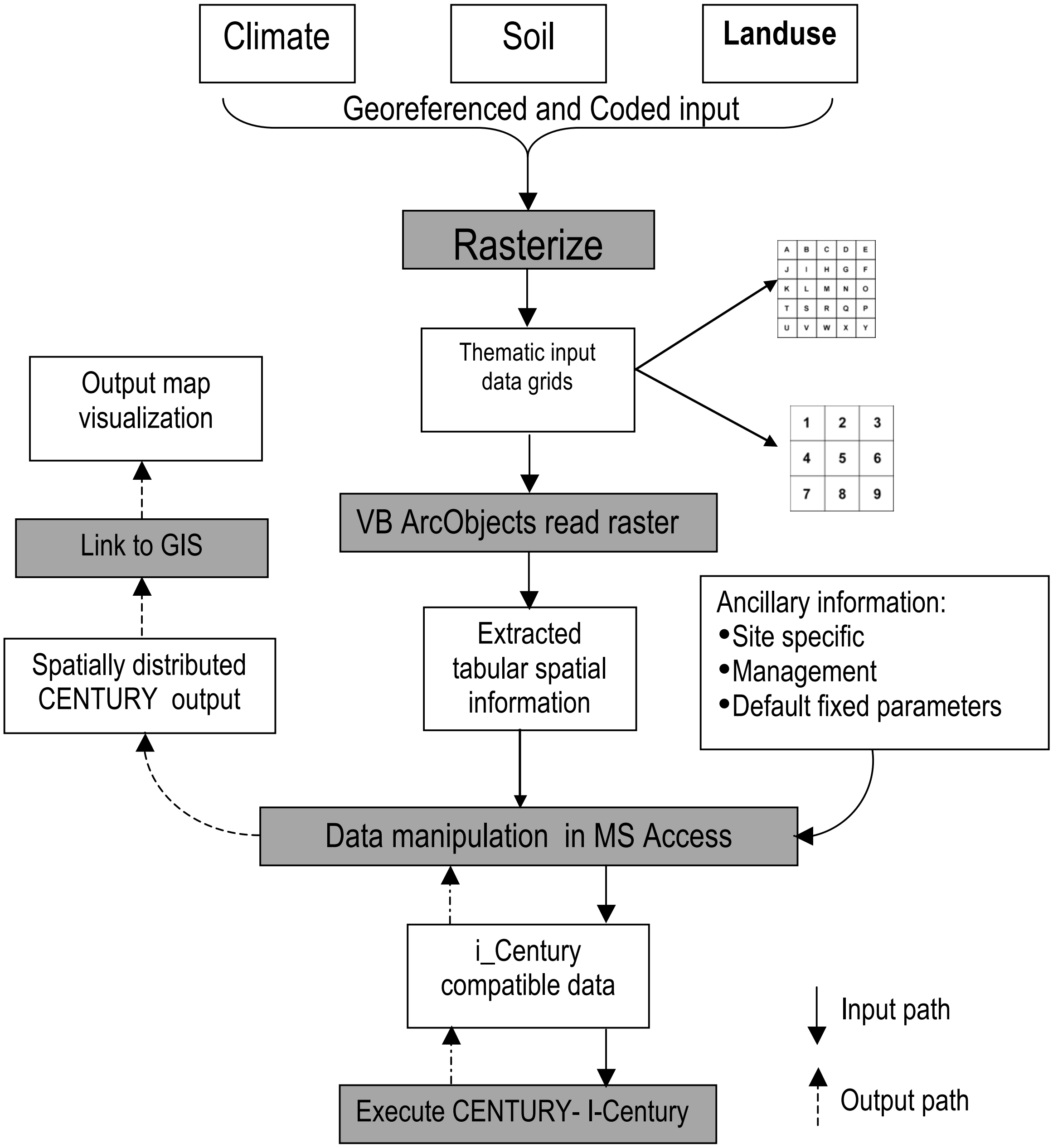

Figure 2. The conceptual framework for regional simulation of C dynamics.

2.4.1 Climatic data

Climatic data was provided from Meteorological Department (MD) in Kampala. The data set includes 6 stations, covering about 2/3 of the study area. The time span stretches between 1960 and 2002. Coordinates for each station were obtained from a list provided by MD. The 6 stations were crosschecked for errors, and missing data were replaced by averages of corresponding time and station. Continuous surfaces were obtained from the stations using the Thiessen polygon interpolation method where each point in space is assigned a value similar to that of the closest station. Each Thiessen polygon is represented by the climate station which contains a time series and an average of monthly precipitation and temperature from 1960-2002.

2.4.2 Soils data

A soil map was available for the study area at a cartographic scale of 1:50000 and was produced by the National Environment Management Authority under an Environmental Information Systems project funded by the World Bank. In the map, 52 soil profiles were described in the area and we relied on the bulk density, texture, and nitrogen estimates to populate our study area with these parameters that are need to run the century model. The sample profiles were unevenly distributed in the study area and between soil types. There are two options for making these data continuous: Thiessen polygons and aggregation. Making Thiessen polygons, however, would exclude the information already available in the soil map. Thus the aggregation method was used to stratify the data by the use of the soil map polygons (very high values were regarded as outliers). Averaging the soil samples within the soil polygons provided the best qualified soil texture values obtainable from this data set. Because only few or no samples exist within each available polygon an average was made for the soil types and this average was been applied to all polygons with the same soil type.

2.4.3 Land use: Historical reconstruction of land use

The land use maps were obtained from satellite images as outlined in section 2.2. Information about actual land use management practices, vegetation types as well as land use in the period before 1972 was obtained from other sources such as interviews, literature, historical archives and anecdotal information. The general land use management histories encountered for savanna and agriculture and used in the model simulations are shown in Table 4. Agriculture is assumed to have started around 1920 and thus the spatial pattern from 1972 is extrapolated into the past on the basis of the 1972 map. From the analysis, 16 possible combinations of land use histories were obtained. Before 1920 the whole area is assumed to be savanna. As the area is pastoral the savanna is influenced by grazing. Before the 1950s the grazing intensity is assumed to be low (very little influence on plant production). During the 1950s boreholes were established and the improved conditions are assumed to have influenced the grazing intensity. During the 1960s the grazing intensity therefore rises to moderate (having a linear effect on plant production). The most common tree species and therefore used in the model executions are the Acacia tree and the *Cenchrus* grass (a C4 species) which are available in the century model. The agricultural areas are mostly grown with millet and groundnuts which are the prevailing crops in the area. Today no fallow is practiced and no fertilizer except for some manure in a few cases. Although some fallow is most likely to have occurred in the period 1960 till today, the model was set up to simulate fallow till 1960 only. Agricultural areas left fallow or abolished are simulated the same way as savanna. The land use management histories as described in Table 4 were coupled to the land use codes from Figure 3 in order to make the assumed land use management histories spatially explicit.

Table 4 Land use management history for savanna and agriculture in the study area.

Time Period	Management	Comments
Savanna		
-1800	Natural savanna, Fire event every 10years	Acacia, C4 grasses
1800-1955	Low grazing, (6 months a year) Fire event every 10 years	
1955-1960	Low grazing all year	
1960-1985	Moderate grazing all year	
1986-2004	High grazing all year	
Agriculture		
-1800	Natural savanna, Fire event every 10years	Acacia, C4 grasses
1800-1920	Low grazing, (6 months a year) Fire event every 10 years	
1920-1930	Millet with fallow	2 years of cultivation, 5 years of fallow
1930-1960	Millet/groundnut rotation	2 years of cultivation, 2 years of fallow
1960-2004	Millet/groundnut rotation	No fallow, no fertilizer

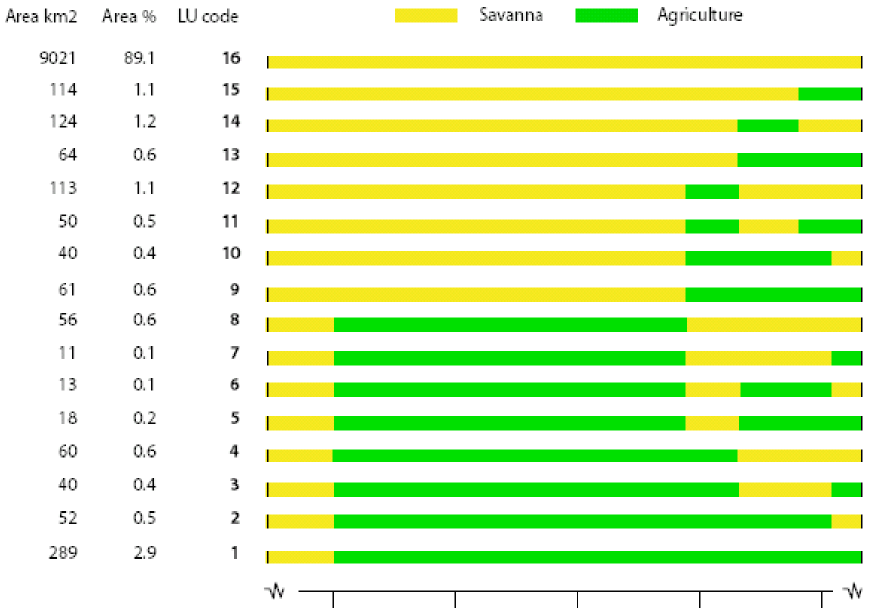

Figure 3. Time line of the 16 land use codes obtained from combining 4 Landsat images.

In addition to land use management histories the Century model also requires details on the exact monthly actions taken from year to year. Table 5 shows detailed monthly land use management as used in our model simulations. A number of variants (not reported here) suiting the different periods were used. For each month, the actual management practice taking place is indicated.

Table 5. Prototype monthly land use management (A) an agricultural year with millet and (B) a savanna year with low intensity grazing.

A: Agricultural year												
Management	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Tree removal	x											
Sowing							x					
Crop growth							x	x	x	x		
Cultivation							x					
Harvest												
Grazing										x	x	x
B: Savanna year												
Tree growth	x	x	x	x	x	X	x	x	x	x	x	x
Crop growth						x	x	x	x	x		
Grazing						x	x	x	x	x		

2.4.4 Results of the simulation

The patterns of soil C in the period from about 1700 up till today is illustrated in Figure 4. A significant portion of total C resides in savanna (covering 89% of the study area). Total C started declining in 1800 when grazing was introduced in the area. After 1920, the level decreased as agriculture is introduced. The total loss is accentuated in Figure 5 and summarized in Table 6 The total C in the entire area decreased by approximately 18 % from 16.9 Mt C before human interference (1800) to 13.8 Mt C in 2004, equivalent to a loss of about 3 Mt C. Of this loss, 70% is attributed to grazing while the other 30% is attributed to agriculture. The Century model simulates C contents up to 20 cm's depth only. This means that losses from the lower layers are not considered but could potentially add another 30-70 %, although these are pools least influenced by human activities.

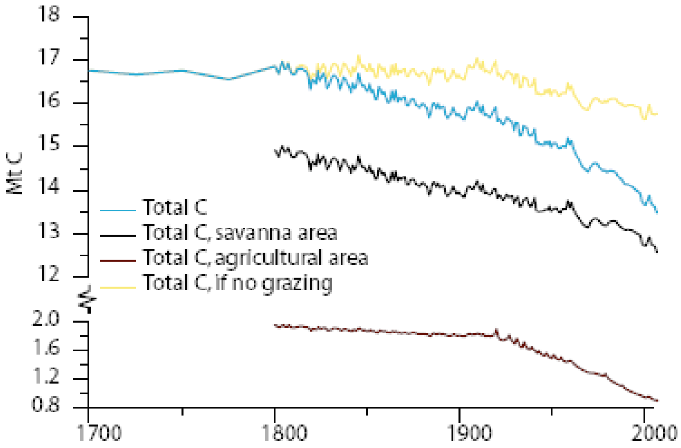

Figure 4. Total C in the study area

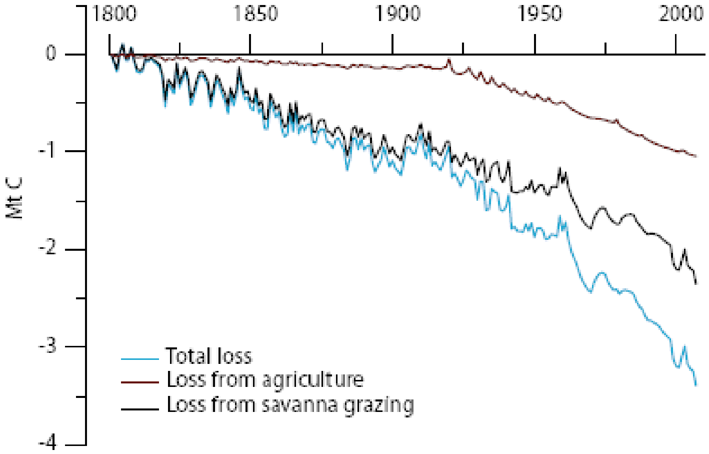

Figure 5. Total C loss in the study area

Table 7. Total loss of carbon split by grazing and agriculture 1800-2004

Period	Cause	% Change	Change (Mt)
1800-1920*	Grazing	-5.6	-0.947
1920-2004	Grazing	-6.6	-1.107
1920-2004	Cultivation	-5.7	-0.955
Total		-17.9	-3.003

* 1800- level is 16.86 Mt C

2.4.4.1 Average C for selected land use histories

The average contents are interesting in an attempt to illustrate the influence of various land use trajectories and land use practices on the carbon level in the area. The study area was represented by 16 different land use histories (Figure 3). One (LU code 16) is permanent savanna and the remaining 15 (LU code 1 to LU code 15) are influenced by cultivation for varying periods of time since 1920 (Figure 6). Carbon contents for 7 of these land use histories, representing general land use trajectories, are outlined in Figure 6.

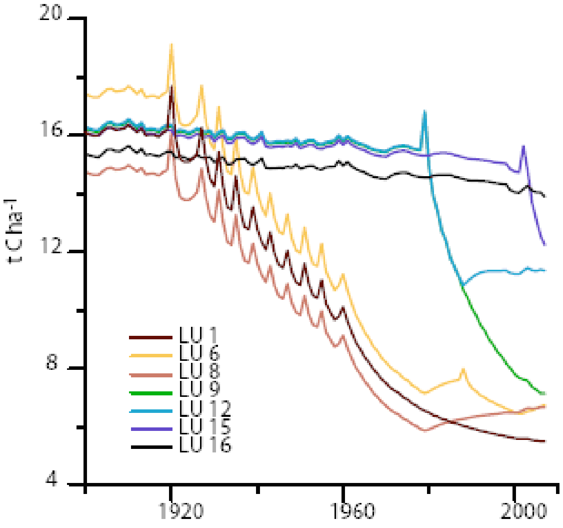

Figure 6. The development of average carbon content in t ha^{-1} for 7 selected land use histories.

LU 1 is the land use history with the longest cultivation history (land was cleared in 1920) causing the first peak due to the release of carbon from felled trees. The following fluctuations of "tooth-like" cycles are caused by the recurring land use practice of two years cultivation followed by two years fallow with grazing.

After 1960, the system exhibits exponential C loss as agricultural lands are permanently cultivated. This caused rapid C losses up to about 1980 after which C losses become relatively attenuated. We postulate that the exponential C decrease reflects C losses from the active pool (with turnover rates of 1-5 years) and that the curve deflection after 30-40 years indicates that the active pool gets depleted and C loss is becomes dominated by the slow and passive pools (Batjes, 1999) whose turnover rates are 10-50 and 400-4000 years respectively.

LU 12 illustrates how fast the C content declines when virgin land is brought under permanent cultivation. 31 % of the C is lost within the first 10 years and 47 % is lost within the first 20 years. This reflects the rapid decomposition rate of the active pool when disturbed. The remaining land use histories outlined are all cultivated for varying periods. LU 6, for instance, is cultivated from 1920 till 1979 where it is left fallow under fallow, reclaimed in 1988 and once again left to fallow in 2004.

2.4.4.2 Scenarios

A number of scenarios were simulated to estimate future C stocks, to evaluate the carbon sequestration potential in the study area and to explore the general land use practices capable of improving the soil quality. Figure 7 (A) shows total C as it would develop according to 9 different scenarios (Table 8) simulated from 2005 till 2300, Figure 7 (B) shows average C level trends under 7 different scenarios for land use history 1 (LU 1).

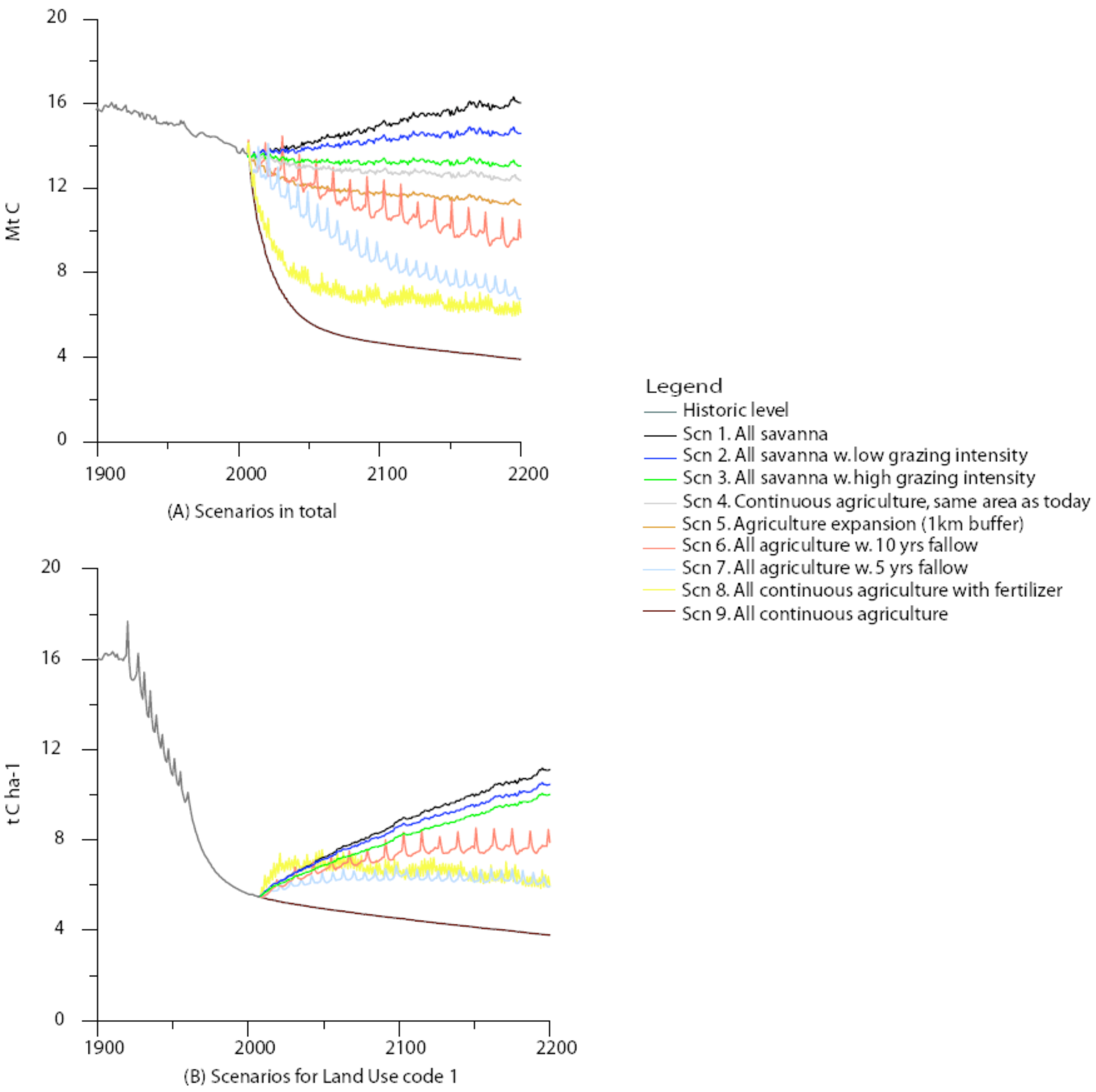

Figure 7. Total C trends (A) and average C levels for land use code 1 (B) according to various scenarios.

Table 8. Hypothetical scenarios simulated from 2005- 2300

Scenario	Type	Management
Scn1	Savanna	No grazing
Scn2	Savanna	Low grazing intensity
Scn3	Savanna	High grazing intensity
Scn4	Agriculture	Continuous millet/groundnut rotation
Scn5	Agriculture	Continuous millet/groundnut rotation
Scn6	Agriculture	10-year fallow, 2 years of cultivation
Scn7	Agriculture	5-year fallow, 2 years of cultivation
Scn8	Agriculture	Continuous millet/groundnut rotation with fertilizer
Scn9	Agriculture	Continuous millet/groundnut rotation

Scenarios 1 and 2 with no grazing and low grazing intensity respectively are the only scenarios that result in a regain of C to the total carbon budget of the study area (Figure 7A). After about 200 years, total C reaches the 1900-level and after 300 years the total C reaches pre-human influence levels (scenario 1). All the remaining scenarios cause a decline in total C (Figure 7 A). Scenario 9, where the entire area is cultivated, is the most extreme where a loss of about 59 % total C is experienced within 50 years. In the 10-year fallow (Scn 6) 12% of the total C would be lost in 50 years.

Figure 7 B shows trends of average C levels for the areas that have been permanently cultivated up to today (land use code 1). The Figure is illustrated with 7 different scenarios (scenario 4 and 5 equals scenario 9). All of the scenarios, except scenario 9, result in an average increase of carbon of between 0.9 and 3.5 t ha^{-1} within 100 years. This indicates that there is potential for carbon sequestration in areas under permanent cultivation. Although none of these scenarios replenishes C to pre-human influence levels, the results are interesting in light of the resilience of the ecosystem and the possible future land use practices. For instance, applying fertilizer (Scn 8) leads to a rapid increase in C levels, peaking after 50 years and then slowly declining again. On the contrary, implementing a 10 or 5 year fallow period causes a slow increase in soil C but then reaches a steady state level higher than or at the same level as that where fertilizer was applied.

2.4.4.3 Spatial distribution of carbon

An extracted time series of the spatial distribution of carbon in the study area is presented in Figure 8 and 9. The maps have been categorized into 10 classes with 2.5 t ha^{-1} intervals for easy visualization but at the expense of loosing more subtle C dynamics. The 1900-level map shows the pre-cultivation situation and thus the patterns in the map can only be caused by influence of grazing, soil types, precipitation and minimum and maximum temperatures.

In 1920, when initial cultivation is assumed to take start, the carbon level rises in the agricultural areas as a consequence of immediate release of carbon from forest clearing and fire (Figure 8 D) (Brady and Weil, 1999). From 1920 to 1960 the agricultural areas gradually loose C to levels lower than the surrounding areas. From 1960 to 2001 the carbon levels of the agricultural areas more or less remain within the same interval.

For the savanna areas the simulated low grazing intensity up to 1955 does not stand out in the maps till 1945. The areas changing in the 1945 map coincide with the borders of precipitation and the temperature zones which suggests (Figure 9 C) that this change is caused by a subtle mix of precipitation and temperature combined with the grazing. From 1960 to 1975 a general decrease appears in the savanna areas as the grazing intensity increases. Several factors influence the dynamics in this map, especially the red brown soils become demarcated but also the precipitation zones in the northern part of the area stand out. The red brown soils have slightly less clay contents compared to the surrounding ferruginous tropical soils, and, in a combination with the specific precipitation and temperatures occurring in the zones (as well as the historical weather data), the enhanced grazing intensity lowers the carbon level in a manner that makes the red brown soils stand out.

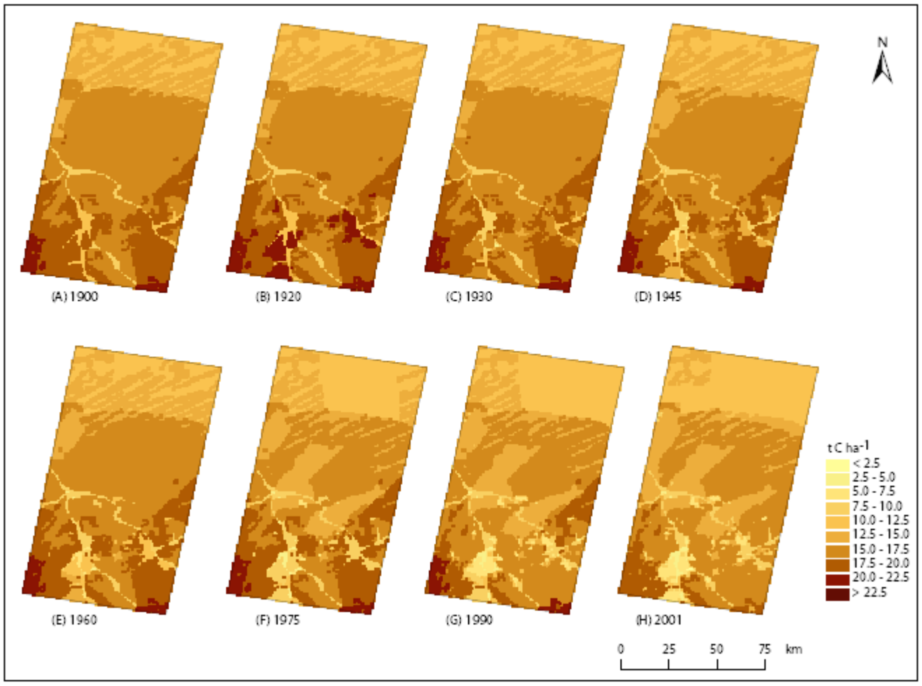

Figure 8. Selected time series of the spatial distribution of soil C from 1900 to 2001

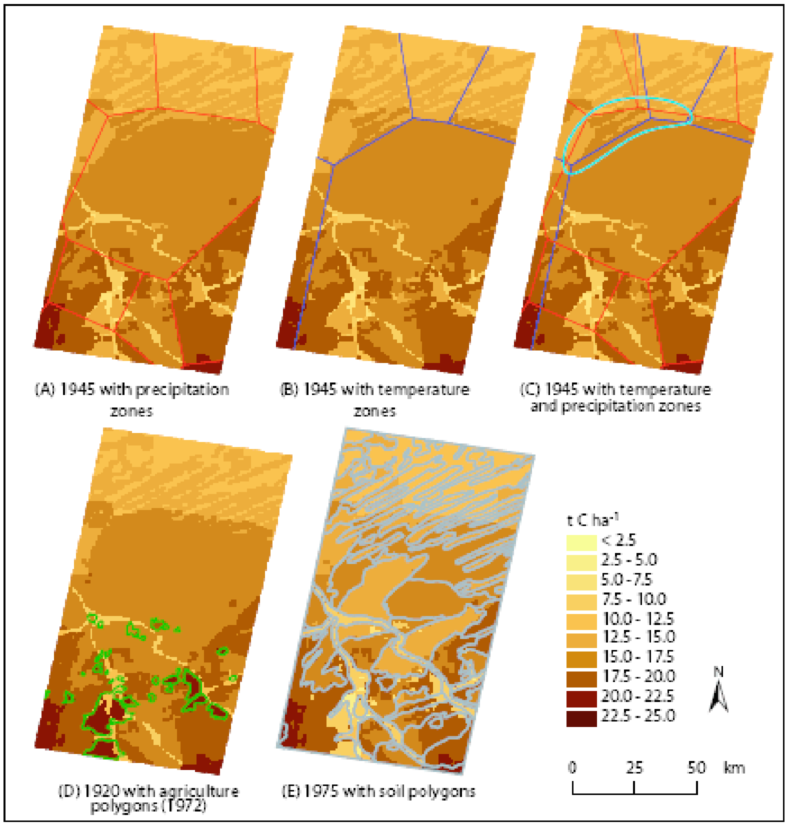

Figure 9. Three output maps overlaid with (A) precipitation zones, (B) temperature zones, (C) temperature and precipitation zones, (D) agriculture polygons and (E) soil polygons.

Selected References

Batjes, N. H.,1999. Management options for reducing CO2-concentrations in the atmosphere by increasing carbon sequestration in the soil. Report 410-200-031, Dutch National Research Programme on Global Air Pollution and Climate Change & Technical Paper 30, International Soil Reference and Information Centre, Wageningen.

Brady, N. C. and Weil, R. R., 1999. The nature and properties of soils, pp. 446-490. Prentice Hall, New Jersey.

Haas, H.J., Evans, C.E. and Miles, E.F. (1957). Nitrogen and carbon changes in Great Plains soils as influenced by cropping and soil treatments. U.S. Dep. Agric. Tech. Bull. No. 1164.

Howden, S.M., McKeon, G.M., Reyenga, P.J., Scanlan, Carter, J.O. and White, D.H. (1995). Management options to reduce greenhouse gas emissions from tropical beef grazing systems. Report for the Rural Industries Research and Development Corporation.

McKenzie, N., Ryan, P., Fogarty, P. and Wood, J. (2000). Sampling, Measurement and Analytical Protocols for Carbon Estimation in Soil, Litter and Coarse woody debris. National Carbon Accounting System Technical Report No. 14. Australian Greenhouse Office, Canberra.

Russell, J.S. and Williams, C.H. (1982). Biogeochemical interactions of carbon, nitrogen, sulfur and phosphorus in Australian agroecosystems. In Galbally , L.E. and Freney, J.R. (Eds.) The Cycling of Carbon, Nitrogen, Sulfur and Phosphorus in Terrestrial and Aquatic Ecosystems. Australian Academy of Science: Canberra.