A Spatio-Temporal Based Estimation of Sequestered Carbon in the Tarkwa Mining Area of Ghana*

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Abstract

The vegetation in the Tarkwa Mining Area (TMA) has experienced changes as a result of population growth, urbanization, mining activities and illegal chainsaw operations and this has led to an increase in temperature over the past years. Therefore, studying its forest biomass carbon (C) stock and its spatio-temporal change is important to the sustainability of forest resources and understanding of the forest C budget in the TMA. In this study, aboveground forest biomass/carbon stock and its changes in the TMA were estimated from three nested-circular plots of horizontal radii 12.62 m, 8 m and 4 m using stratified random sampling from sixty locations in five land use/cover types as well as GIS/Remote Sensing techniques over a 21 year period. An estimated total of 1 250.93 ± 7 Mg/km^2 carbon was recorded in the TMA. Carbon in different land-use/cover types ranges from 587.76 ± 4 Mg/km^2 carbon in closed canopy to 270.23 ± 2 Mg/km^2 carbon in shrubs/herbaceous. The TMA also experienced an average of 412.14 Gg of carbon (equivalent to 19.63 Gg carbon per year) lost between 1986 and 2007 due to the changes in the land use/cover types. The study area is however, considered a net source of carbon.

Keywords: Spatio-Temporal, Carbon, Mining, Biomass, GIS

1 Introduction

The United Nations Framework Convention on Climate Change (UNFCCC), endorsed by forest-rich countries, to include economic incentives in the Kyoto Protocol, marked the genesis of Reduced Emissions due to Deforestation and Forest Degradation (REDD) mechanisms in many countries. The REDD mechanisms are aimed at offering financial incentives to motivate countries to freely reduce national deforestation rates and associated carbon emissions below a baseline, be it historical or future. Countries can therefore trade their emissions reduction for carbon credit on the International Market. It is expected that the reduction in carbon emissions due to deforestation and forest degradation may lead to climate change mitigation, conservation of biodiversity, and protection of ecosystem services and goods (Gibbs *et al*., 2007).

Estimates of carbon stocks in tropical ecosystems are of high relevance for understanding the global carbon cycle, the formulation and evaluation of global initiatives to reduce global warming, and the management of ecosystems for carbon sequestration purposes. However, detailed knowledge about the location, absolute and relative distribution of carbon stocks in tropical forests is still limited (Clark, 2004; Houghton, 2005). Estimating carbon stocks and their distribution in different ecosystem pools is important to understand the degree to which carbon is allocated to labile and stable components. This information is also useful in estimating the amount of carbon that is potentially emitted to the atmosphere due to land use changes as well as from natural or artificially induced fire events. In the tropics, estimates of carbon stocks using ground-based measurements are usually focused on quantifying the aboveground component (Houghton, 2005), while *necromass*, and the spatially allocated carbon stocks are seldom measured. Although estimations of forest biomass are abundant in the tropics, it can be inferred from Houghton *et al.* (2001) that there are several problems in published estimates of carbon stocks from ground-based measurements. These include the: uncertainty associated with spatial variability, lack of distinction between primary and secondary forests, small inventory areas (< 1 ha), incomplete measurements of carbon pools, biased sample designs, inadequate use of regression equations and lack of continuity in surveys. A secondary forest has been estimated as an important component of land cover area in the tropics and for this reason they play an important role in the carbon balance of the world (Brown and Lugo, 1990). According to the Food and Agriculture Organisation (FAO), in 1990 secondary forests accounted for 335 million ha in Latin America (Sierra *et al*., 2007). In Colombia, secondary forests are an important fraction of total forested area and their distribution is highly heterogeneous, mixed with croplands, grasslands, and primary forests (Etter and van Wyngaarden, 2000).

Several studies have estimated biomass carbon stocks for forests. For example, Fang *et al.* (2001) calculated total living forest biomass storage and its change based on historical forest inventory data; using a process-based equilibrium terrestrial

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biosphere model, BIOME3, while, Ni (2002) simulated distribution of forest biomass stocks. However, the former failed to present detailed and spatially explicit analysis on forest biomass carbon density (carbon stock per hectare) because only information on forest growth for each of the forest type for each area was available. However, Ni (2002) just provided the potential estimation because climate based ecosystem model only takes climate variables as the impact factors of forest growth, without considering anthropogenic disturbances such as farming, illegal chainsaw operations, urbanisation, population growth and mining activities as a result of land use change dynamics. Accordingly, this paper seeks to explain the potential of incorporating satellite image in estimating carbon stocks spatially.

Satellite data provide information on the integrated responses of plant growth to environmental factors, including natural and anthropogenic disturbances. Over the past decade, satellite data have been widely used to explore changes in forest biomass at regional and global scales, because they have provided consistent global vegetation coverage at relatively high spatial resolution since the early 1980s (Myneni *et al.*,2001; Tucker *et al.*, 2001; Zhou *et al.*, 2001; Dong *et al.*, 2003).Compared to previous direct field measurements and inventory-based estimation, integrated estimation using remote sensing and inventory data can exhibit spatially explicit patterns of forest biomass and its temporal change.

The Tarkwa Mining Area (TMA), the focus of this paper, has experienced increase in temperature over the last decade. Drier and warmer climate in the future has been predicted. Studies conducted elsewhere suggest that changes in climate have substantial effects on vegetation growth (Chen, 2002; Jiang *et al.*, 2002; Ni, 2002; Fang *et al.*, 2003; Piao *et al.*, 2005). To date, however, there have been no studies to estimate the forest biomass carbon for the TMA by using remote sensing data. Therefore, the primary objective of this study is to investigate explicit patterns of forest biomass (aboveground and *necromass*) and its temporal change in the TMA.

2 Materials and Methods Used

2.1 Study Area

Fig. 1 shows the location of Tarkwa-Nsuaem Municipality and its environs (the study area) in the Western Region of Ghana. For the purpose of this paper, it shall be referred to as the Tarkwa Mining Area (TMA). TMA is located between latitudes 4˚0' 0" N and 5˚40'0" N and longitudes 1˚45'0" W and 2˚1'0" W. The area is estimated to have a total land area of 3 783.64 km^2 with Tarkwa having a population of 40 397 inhabitants as of 2005 (Kumi-Boateng, 2010). TMA has nearly a century of gold mining history and has the largest concentration of mines in a single area in Africa, with virtually all the six new gold mines operating surface mines (Akabzaa, 2001). TMA was the focus of attention by the earliest European prospectors and promoters who first entered the hinterlands of the Gold Coast Colony in the late 1870s just after the region had been declared a British colony (Griffis *et al*., 2002). It eventually became an important gold producing area and an administrative centre for the mining industry. Underground mining was carried out for over 100 years during which about 7 million ounces of gold were produced. However, from the late 1960s to the mid 1980s, production of gold in the area dropped drastically due to a variety of problems. Revival of gold mining started in the late 1980s when attention was focused on the open pit potential of the area (Griffis *et al*., 2002).

TMA lies within the South-Western Equatorial Zone. It therefore has fairly uniform temperature, ranging between 26˚C in August and 30˚C in March. It has a mean annual rainfall of 187.83 cm with a double maximum rainfall starting from March and September as the main rainfall season and October to February as the dry season. The TMA falls within the rainfall belt with evergreen equatorial vegetation. Economic trees include mahogany, wawa, odum and sapele (Anon., 2010). In recent times, most parts of the rich forest have been reduced to secondary forest through increased human activity. Human activities such as, open pit mining, farming and indiscriminate lumbering have impacted negatively on the natural vegetation. However, the TMA can still boast of large forest reserves like the Bonsa Reserve (209.79 km^2), Ekumfi Reserve (72.52 km^2) and Neung Reserve (157.84 km^2).

Four land use/land cover maps from a previous study by Kumi-Boateng *et al.* (2011) were used to estimate the various land use/land cover areas. Topographic map at a scale of 1:50 000 of the area obtained from the Mapping and Survey Division of Ghana were also used. Secondary data on the vegetation composition in the study area was obtained from the Forestry Commission of Ghana.

Navigation to the plot and recording of the centre of the sample plots was done using Garmin GPS. The diameters of the trees in the area were measured with vernier calliper and a tape.

Land use/land cover data were interpreted and digitized from the digital images into ESRI shape files in the Ghana National Grid (GNG) coordinate system. Statistical analyses were done using R software and the Analysis Toolpak function of Microsoft Excel. Spatial distribution of allocated carbon stocks within the various land use/land cover types was done using ArcGIS.

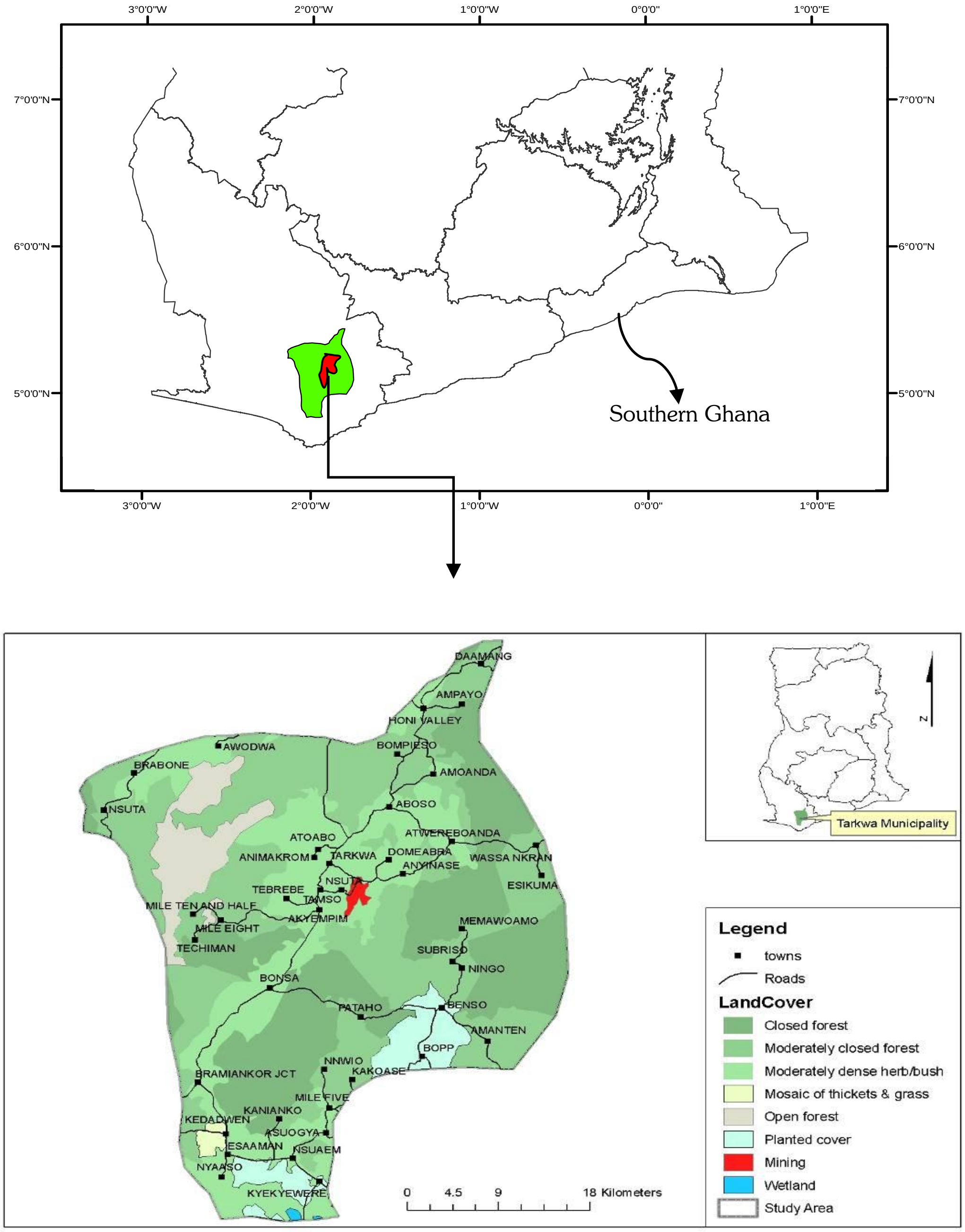

Fig. 1: Tarkwa Mining Area (TMA)

2.2 Materials

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2.3 Methods

2.3.1 Sampling Design

In view of time and logistic constraints biomass inventory was restricted to aboveground biomass and necromass. This was defined to include aboveground live tree biomass and herbaceous plants (plants and litter) referred to here as necromass. In this study, the limited resources was focused on the aboveground living tree biomass because trees typically constitute the major pool, and are the most directly affected by forest loss (Gibbs *et al.*, 2007). Below ground biomass and dead woody components were not considered. Consequently, the emission estimates may be lower than the real emissions because emissions could come from the other pools. A stratified random sampling was used for the biomass inventory, and consequently the estimation of sequestered carbon. This was necessary to capture the variations between the different land use/land cover types. A land cover map of 2007 was used to facilitate stratification of the study area.

In all, biomass inventory was conducted in 60 plots distributed in the five dominant cover types. Eight plots were selectively established in each land-use/cover type to ensure even distribution of plots among the land-use/land cover types. Each sampling site comprised three-nested circular plot of 12.6 m, 8 m and 4 m radii respectively as shown in Fig.2.

The purpose of the three nested circular plot design was to ensure highly variable representation of live woody-plants of different ages and also reduce double counting. The Intergovernmental Panel on Climate Change (IPCC), recommends the use of three-nested circular plot design for carbon inventory in tropical ecological conditions where tree-age heterogeneity is dominant (Anon, 1997b).

Circular plots were employed because they are quick and easy to layout in the field. Additionally, enumeration of trees is easier than square plots. In each plot, all woody trees ≥5 cm Diameter at Breast Height (DBH) were identified for species, measured for DBH and recorded. Specifically, trees >50 cm DBH were inventoried in the larger plots.

Trees 15 cm to 50 cm DBH were measured in the 8 m radius plots. Smaller diameter trees (*i.e.* those ≥ 5 cm and < 15 cm DBH) were enumerated in the smaller plots (4 m radius). Diameter measurements were taken using vernier calliper and diameter tape. Spatial information, including the coordinates, elevation and slope were recorded for each plot.

2.3.2 Aboveground Live Tree Biomass Estimation

The IPCC prefers locally developed biomass equations as research indicate that equations developed elsewhere may result in very high errors (Dwomoh, 2009). However, there are currently no local allometric equations developed for Ghana's forests. No attempt was made to develop one in the course of this research, as that is beyond the scope and resources of this paper. Hence, aboveground tree biomass was estimated using FAO (Anon, 1997a) recommended allometric equation for moist tropical forest zones (1 500 – 4 000 mm rainfall/year) in Africa shown in *Equation 1*.

$$Y\left(\text{kg tree}^{-1}\right) = \exp^{(-2.134+2.53\ln \text{DBH})} \qquad (1)$$

where:

Y = Aboveground tree biomass in kg

DBH = Diameter at breast height, cm

In order to ascertain the results of aboveground tree biomass, other biomass equations developed for specific countries of similar tropical conditions were used to assess the range of uncertainty of estimated biomass.

2.3.3 Non-Tree Vegetation Carbon Pool

For the estimation of biomass in non-tree pools, destructive sampling technique was used. Two small squared subplots of size 0.25 m^2 (0.5 m x 0.5 m) were established in each plot location for sampling of herbaceous biomass (plant and litter) (Anon, 2003). In each subplot all non-tree pools were clipped at ground level, collected and weighed for fresh weight.

A well-mixed subsample (subsample fresh mass) from each sample were weighed and oven dried to a constant mass (subsample dry mass) at 100 ˚C for 48 hours in the laboratory. Dry-to-wet mass ratios were determined for the subsamples. These ratios were used to convert the entire sample to oven-dry matter (Cummings *et al.*, 2002). Following Cummings *et al*., (2002) and Pearson and Brown (2004), the dry mass of the samples (from which subsample were oven-dried) were computed using Equation 2.

$$\text{DM} = \left(\frac{\text{SSDM}}{\text{SSFM}}\right) \times \text{FMW}S \qquad (2)$$

where:

DM = Dry mass;
SSDM = Subsample dry mass;
SSFM = Subsample fresh mass and
FMWS = Fresh mass of whole sample

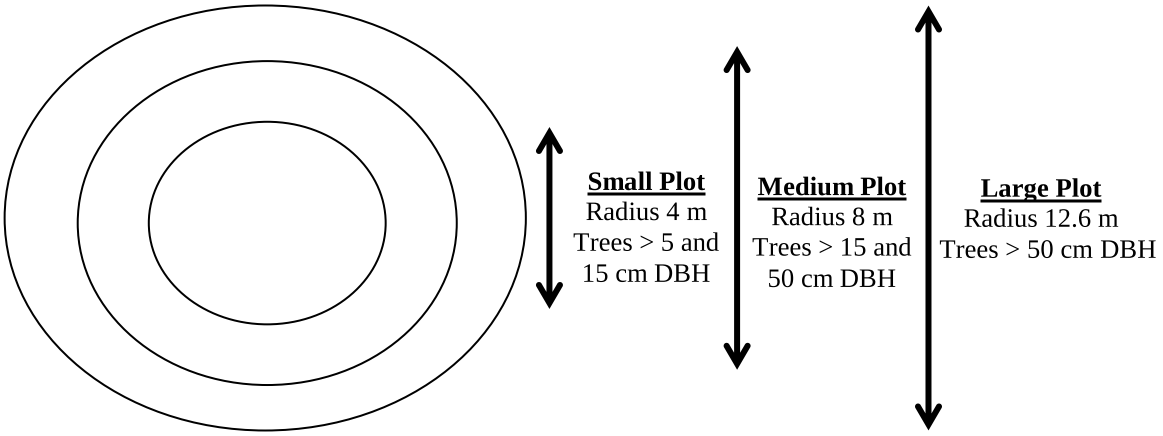

Fig. 2 Three Nested Circular Plot Sampling Design (adopted from Anon, 1997b)

The dry mass calculated for a particular non-tree vegetation pool was extrapolated to obtain the biomass density (Mg/km^2) for that pool. Hence the sum of biomass densities of non-tree vegetation pools yielded the non-tree component biomass density for that plot.

2.3.4 Aggregation and Up-Scaling of Total Sequestered Carbon

The plot tree biomass density values were converted to tree carbon stock (kg.km^{-2}C) by multiplying by carbon fraction of biomass. A biomass-to-carbon conversion factor of 0.5 was used (Nascimento and Laurance, 2002; Anon, 2003; Pearson and Brown, 2004; Gibbs *et al.*, 2007).

The same conversion factor was used to obtain the carbon densities (Mg.km^{-2}C) of the non-tree vegetation pools (Pearson and Brown, 2004). Finally the carbon density for each plot was obtained by summing up all the carbon densities (for trees and non-tree components) for each plot location.

The mean carbon density per cover type was obtained by averaging the carbon densities of all sample plots in a particular cover type. Consequently, the total sequestered carbon (Gg) per cover type was estimated by multiplying its average carbon density by the total area of that cover type. Therefore, the overall sequestered carbon of the study area was computed by summing the total sequestered carbon of the different cover types.

2.3.5 Spatially-Based Analysis of Sequestered Carbon

Spatially-based analysis of sequestered carbon was done in GIS environment. Using interval-method, allocated carbon density of each land-use/land cover type was calculated for 1986, 1990, 2002 and 2007.

With this carbon density (Gg), each raster was spatially assigned a carbon density depending on the land-use/land cover type in GIS with 500 m grid size.

Using the Raster Calculator in ArcGIS, five rasters, with each containing the various carbon densities for the pixels that fall into a certain land-use/land cover category, were extracted for years 1986, 1990, 2002 and 2007. The sum of all the individual land-use/land cover layers yields the carbon sequestration map.

3 Results and Discussions

3.1 Results

Results of the spatial distribution of sequestered maps of the TMA are stated in the following subsections.

3.1.1 Distribution of Sequestered Carbon in Different Land-Use/Cover Types

Table 1 summarises the results of the calculated values of land use/land cover allocation of mean sequestered carbon. An estimated mean of 410.31 ± 9 Mg/km^2 carbon was recorded in the TMA. Carbon in different land-use/land cover types ranged from 587.76 ± 4 Mg/km^2 in closed canopy to 270.23 ± 2 Mg/km^2 in shrubs/herbaceous. Closed canopy areas recorded 390.94 ± 3 Mg/km^2 carbon while settlement and mining areas were considered insignificant in terms of carbon uptake.

In the closed canopy areas, 47 .19% of carbon is stored in live tree biomass compared to 30.95% of carbon in non-tree vegetation. Carbon stocks in non-tree vegetation pools in all the land-use/land cover types ranged from 3.89 % in shrubs/herbaceous areas to 4.23% in open canopy areas. In general, all the closed canopy areas were found to contain more sequestered carbon.

3.1.2 Total Carbon Sequestration within Land-Use/land Cover Types

In 1986, a total of 885.46 Gg carbon was sequestered in the study area as compared to 726.31 Gg carbon in 1990. Closed canopy areas recorded the highest carbon storage of 584.61 Gg carbon in 1986 representing 66.02% while in 1990 a total of 396.79 Gg carbon were stored in open canopy areas (Table 2). Shrubs/herbaceous increased its carbon allocation from 27.98 to 90.44 Gg representing 3.16% and 12.45% in 1986 and 1990 respectively.

By 2002, a total of 1 192.69 Gg carbon had been sequestered in the study area as compared to 473.32 Gg carbon in 2007 (Table 3). Closed canopy areas experienced a reduction in carbon stocks from 202.87 to 59.26 Gg Carbon.

Due to the stress the TMA has been subjected to by the land use/land cover dynamics, there was a general reduction in the amount of carbon sequestered in the various cover types from 2002 to 2007.

It was observed that over the 21 year period under study, closed canopy which is mainly rain-forest with three layers of multiple species obstructing sunlight from reaching the floor experienced a consistent decrease in the total sequestered carbon whereas the other cover types experienced fluctuations in carbon storage (Fig. 3).

3.1.3 Spatial Distribution of Sequestered Carbon

The spatially-based analysis revealed that more areas to the north-eastern and south-western parts of the study area, where vegetation is relatively least disturbed sequestered more carbon in both 1986 and 1990 (see Figs. 4a and 4b).

By 2002, the vegetation within the TMA had become labile as a result of population growth, increase mining activities and urbanization (the white large patches in figure 4c are mining and settlement areas) reducing the amount of carbon sequestered in both closed and open canopy.

In the 2007 sequestered carbon distribution map (Fig. 4d); the amount of carbon in both closed and open canopy had been reduced as a result of disturbance with shrubs/herbaceous cover type which spreads across the entire study area taking over as the major carbon pool.

However, the white patch grids are areas under settlement and mining areas, and here carbon uptake is considered insignificant. The high carbon sequestered in both closed and open canopy is more dominant in 1986 than in 2007.

Table 1 Land-Use/Land Cover Allocation of Mean Sequestered Carbon

Cover Type	Aboveground Biomass		Non-Tree Vegetation		Total Carbon	
	Mean (Mg/km^2)	%	Mean (Mg/km^2)	%	TC (Mg/km^2)	%
Closed Canopy	588.12	47.19	3.64	30.95	591.76	47.04
Open Canopy	389.71	31.27	4.23	35.97	393.94	31.32
Shrubs/herbaceous	268.34	21.53	3.89	33.08	272.23	21.64
Mining Areas	0.00	0.00	0.00	0.00	0.00	0.00
Settlement	0.00	0.00	0.00	0.00	0.00	0.00
Total	**1246.17**	**100.00**	**11.76**	**100.00**	**1257.93**	**100.00**

Table 2 Total Carbon Allocation per Land-Use /Cover Type (1986-1990)

Cover Type	Area		Per Unit	Carbon Allocation (Gg)		Percent (%)	
	1986	1990	TC (Gg/km^2)	1986	1990	1986	1990
Closed Canopy	987.91	404.02	0.59	584.61	239.08	66.02	32.92
Open Canopy	692.68	1007.24	0.39	272.87	396.79	30.82	54.63
Shrubs/herbaceous	102.77	332.20	0.27	27.98	90.44	3.16	12.45
Mining Areas	8.00	32.62	0.00	0.00	0.00	0.00	0.00
Settlement	6.28	17.56	0.00	0.00	0.00	0.00	0.00
Total	**3783.64**	**3783.64**	**1.26**	**885.46**	**726.31**	**100.00**	**100.00**

Table 3 Total Carbon Allocation per Land-Use /Cover Type (2002-2007)

Cover Type	Area		Per Unit	Carbon Allocation (Gg)		Percent (%)	
	2002	2007	TC (Gg/km^2)	2002	2007	2002	2007
Closed Canopy	342.83	100.15	0.59	202.87	59.26	22.91	8.16
Open Canopy	893.90	531.10	0.39	352.14	209.22	39.77	28.81
Shrubs/herbaceous	2342.41	752.43	0.27	637.67	204.83	72.02	28.20
Mining Areas	105.08	211.36	0.00	0.00	0.00	0.00	0.00
Settlement	99.42	181.60	0.00	0.00	0.00	0.00	0.00
Total	**3783.64**	**3783.64**	**1.26**	**1192.69**	**473.32**	**134.70**	**65.17**

3.1.4 Changes in Land-Use/Land Cover Types and Carbon Sequestration

To further estimate the effect of land use/land cover change on carbon stocks, the annual change rate of sequestered carbon was calculated from 1986 to 2007 under different land use/land cover types using 1986 as a base year. The results are summarised in Table 4. The results show that an average of 412.14 Gg of carbon (equivalent to 19.63 Gg carbon per year) was lost between 1986 and 2007 due to changes in land use/land cover types.

The study area is, however, considered as a net source of carbon. From Table 4, closed and open canopy are considered key carbon emission sources compared to shrubs/herbaceous cover type, which served as emission reduction sinks between 1986 and 2007. Closed canopy areas had the highest loss of 525.34 Gg carbon (25.02 Gg carbon per year) followed by open canopy with 63.65 Gg carbon (equivalent to 3.03 Gg carbon per year) emissions. In 2007, shrubs/herbaceous areas sequestered 176.86 Gg carbon more relative to 1986. Similarly, open canopy and shrubs areas in 2002 sunk more carbon than in 1986 (*i.e.* 79.27 Gg carbon and 609.7 Gg carbon respectively) as shown in Table 4.

3.2 Discussions

3.2.1 Carbon Stock Budget in Different Land-Use/Land Cover Types

Differences in net carbon stocks for various land-use/land covers support the hypothesis cited by Sharma *et al*.(2007) that land-use/land cover transformation from vegetation to agriculture and other usage causes tremendous loss of carbon stocks. The relatively high amount of carbon stocks in closed canopy (591.76 Mg/km^2) compared to other land-use/land cover types as depicted in Table 1 confirm Houghton (1999) assertion that forests contain 20 to 100 times more biomass carbon per unit area than that of other cover types. The estimate of 587.76 ± 4 Mg/km^2 carbon for closed canopy in this study is among the largest recorded in tropical regions including those values reported by Glenday (2006), Woomer (2004), Sharma *et al*. (2007) and Sierra *et al*. (2007). The results indicate that natural vegetation significantly sequesters more carbon compared to other land-use/land cover types. This is because tropical vegetation is perceived to contain remarkably diverse and a high density of active vegetation and soil carbon pools. These active pools also facilitate high net primary productivity (NPP) in forest more than other land-use/land cover types. This is consistent to the high NPP value (1 000 gC/m^2/year) reported for tropical seasonal forest by Klein *et al.* (1994) relative to other vegetation types.

Total sequestered carbon in open canopy areas which is predominantly secondary re-growth, other trees with no overhead canopy and a crop farm with mixture of crops, is a little over half of that of the closed canopy. The main reason for this difference could be due to relatively high NPP fixed in forest areas compared to farm areas. In addition, decomposition and subsequent release of carbon to the atmosphere are suspected to be high in farm areas probably due to its favorable temperature and relative humidity conditions. This condition facilitates reduction in conversion of litter carbon to stable carbon in soils.

Sharma *et al.* (2007) reported similar carbon stocks in farm areas but the difference is in 100 folds. In the study area, perennial cropping is the most common farming system. However, the perennial crops are usually interspersed with trees, primarily, to provide shade and fertile soil necessary for growth. This practice is likely to have accounted for the relatively higher vegetation carbon in crop farm areas in this study compared to the results reported by Sharma *et al*. (2007).

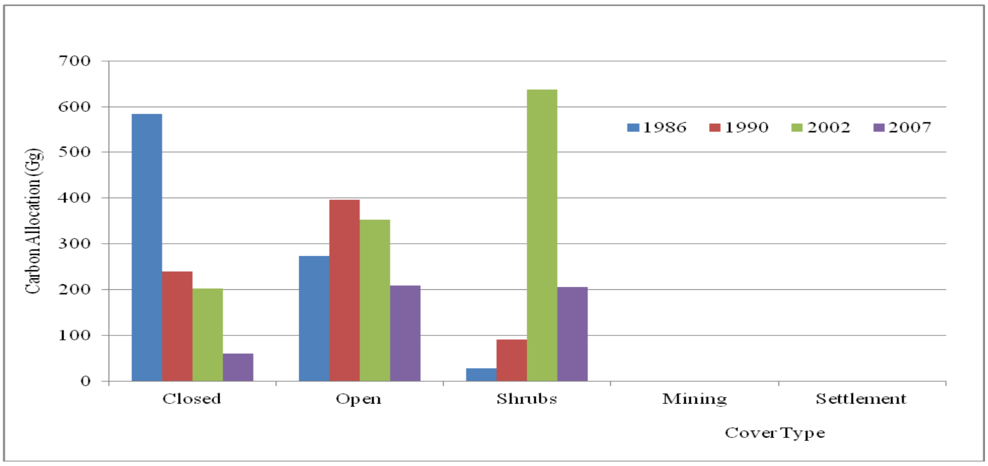

Fig. 3 Total Carbon Allocations per Land-Use /Land Cover Type (1986-2007)

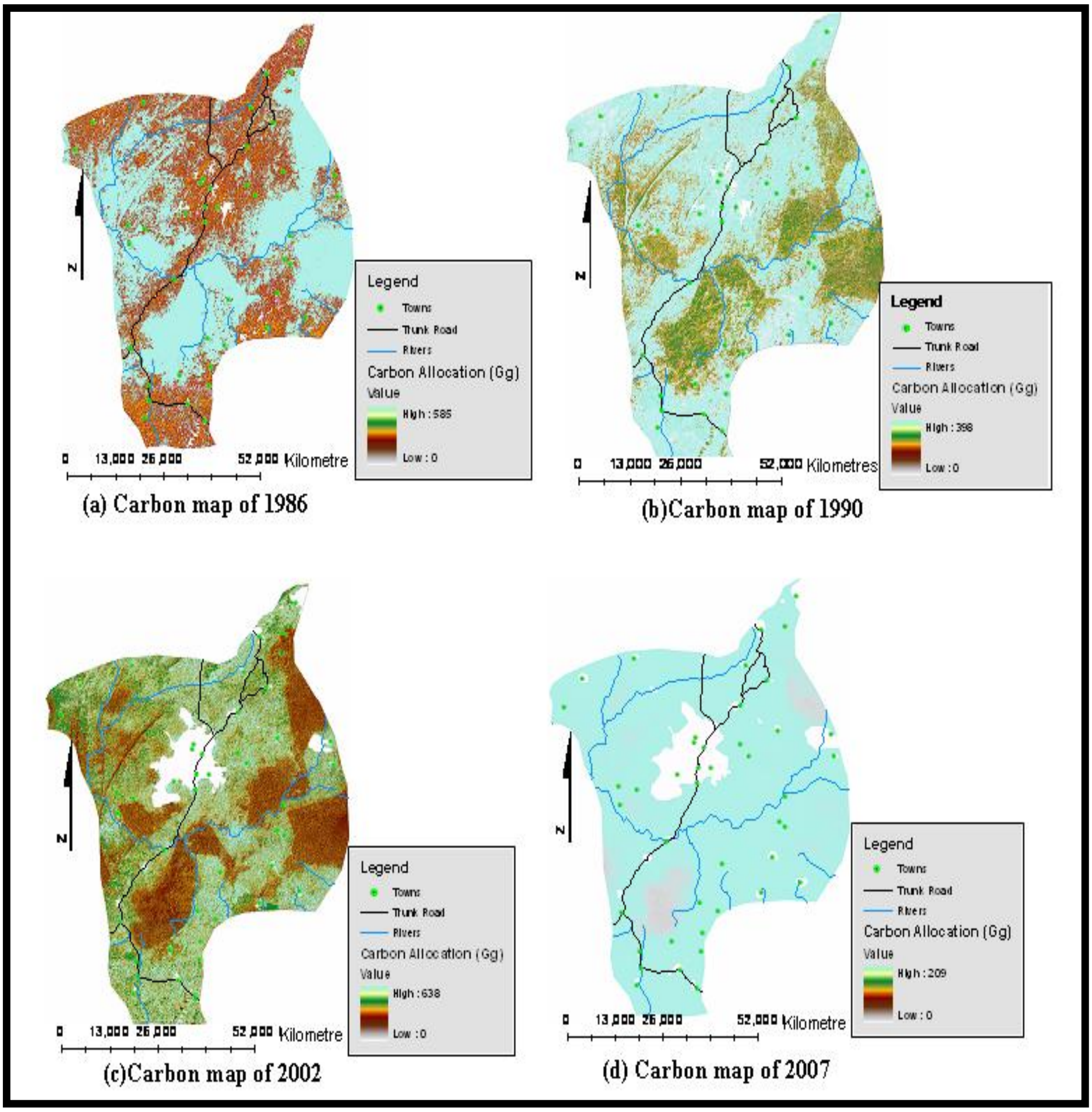

Fig. 4 Distribution of Sequestered Carbon, 1986-2007

Shrubs/herbaceous areas (i.e. areas considered as grass cover and fallow vegetation which dry up in the dry season exposing partly the soil cover, freshly cleared/planted areas of fallowed and access road corridors) sequestered 270.23 ± 2 Mg/km^2 carbon. This observation, though, is the least recorded in this study, it is significantly high compared to previous results obtained by Woomer *et al*. (2004) in the Senegal's transition zone of Africa, particularly due to differences in climatic conditions. The high amount of carbon in the grassland could be attributable to the high foliaging nature of *chromoleana ordorata* and elephant grass common in the study area. The nature of the grass could also facilitate litter carbon transfer through the root systems and decomposition.

Total sequestered carbon (*i.e.* aboveground and non-trees vegetation biomass) in vegetated and non-vegetated areas ranged from 3.89 to 588.12 Mg/km^2. This value falls within the range reported by Woomer (2004), Glenday (2006) and Sierra *et al.* (2007). It is also consistent with the potential aboveground biomass limits modeled for African lowland moist forest by Brown and Gaston (1995). However, various authors like Bonino (2006), Houghton (1999) and Sharma *et al*. (2007) had reported considerably lower results in other tropical regions in Asia.

3.2.2 Changes in Carbon Stocks and Land-Use/Land Cover Types

The conversion of closed and open canopy areas (i.e. 542.79 km^2 and 166.73 km^2 respectively) between 1986 and 2007 to other land use/land cover types contributed to the loss of 412.14 Gg carbon at an annual rate of change of 19.63 Gg carbon per year. This figure is similar to the results obtained by Li *et al*. (2008) in the China Xishuangbanna region. The decrease in total carbon is also consistent with the rate of land-use/land cover change, similar to what Sharma *et al*, (2007) reported. The highest change in carbon stocks resulted from the conversion of closed canopy to shrubs/herbaceous, settlements, mining and farm areas which were subsequently allowed to go fallow over a period of time. This facilitated the replacement of vegetation biomass carbon from closed canopy to shrubs/herbaceous, built-up/mining or farm areas. Though farm areas could maintain certain levels of sequestered carbon after conversion from closed canopy, such areas should be allowed to fallow and in the process accumulate some level of active vegetation biomass which can sequester more carbon in a relatively large area. This accounted for the high carbon stocks (176.86 Gg) in the shrubs/herbaceous areas in 2007 relative to 1986 (Table 4). Apart from the loss of vegetation carbon pools in closed and open canopy areas, the 34% average conversion of closed canopy and open canopy to other land-use/land cover types remarkably influenced the decrease in carbon stocks in the study area.

Table 4: Changes in Carbon Sequestration with Land-use/Land Cover types

Cover Type	**Changes between (Gg):**					
	1986 and 1990	**%**	**1986 and 2002**	**%**	**1986 and 2007**	**%**
Closed	-345.52	-39.02	-381.73	-43.11	-525.34	-59.33
Open	123.92	13.99	79.27	8.95	-63.65	-7.19
Shrubs	62.46	7.05	609.70	68.86	176.86	19.97
Mining	0.00	0.00	0.00	0.00	0.00	0.00
Settlement	0.00	0.00	0.00	0.00	0.00	0.00
Total	**-159.15**	**-17.97**	**307.23**	**34.70**	**-412.14**	**-46.55**
Estimated Total Carbon Allocation for 1986 (Gg)						**885.46**

4 Conclusions

This study integrated vegetation inventory observations and remotely sensed dataset to estimate sequestered carbon and their changes within the various land-use/cover types. Carbon in different land-use/cover types according to this study ranges from 587.76 ± 4 Mg/km^2 in closed canopy to 270.23 ± 2 Mg/km^2 in shrubs and herbaceous. The estimate of 587.76 ± 4 Mg/km^2 carbon for closed canopy in this study is among the largest recorded in tropical regions.

The results indicate that natural vegetation significantly sequesters more carbon compared to other land-use/cover types. This is because tropical vegetation is perceived to contain remarkably diverse and a high density of active vegetation and soil carbon pools. Open canopy areas recorded 390.94 ± 3 Mg/km^2 carbon while settlement and mining areas were considered insignificant in terms of carbon uptake.

The study also shows that, carbon stocks in non-tree vegetation pools in all the land-use/cover types ranged from 3.89 % in shrubs and herbs areas to 4.23% in open canopy areas. However, in the closed canopy areas, 47.19% of carbon is stored in live tree biomass compared to 30.95% of carbon in non-tree vegetation.

The study also concludes that, conversion of closed and open canopy areas (i.e. 542.79 km2 and 166.73 km2 respectively) between 1986 and 2007 to other land use/cover types contributed to the loss of 961.13 Gg carbon at an annual rate of change of 45.77 Gg carbon per year.The decrease in total carbon is also consistent with the rate of land-use/cover change, similar to what Sharma et al. (2007)and Li *et al*. (2008) in the China Xishuangbanna region reported.

The high change in carbon stocks resulted from the conversion of closed canopy to shrubs and herbs, settlements, mining and farm areas which were subsequently allowed to go fallow over a period of time. This facilitated the replacement of vegetation biomass carbon from closed canopy to shrubs and herbs, built-up or mining or farm areas. It is therefore concluded that the rate of land-use/cover change over the four temporal scales causes commensurate loss of carbon stocks. However, the rate of carbon loss becomes emission source if the conversion is from vegetated to non-vegetated areas. Though conversion within different vegetation types releases carbon to the atmosphere, it is reasonably compensated in the new land-use/cover type over time.

Finally, the future of REDD and related climate policies need not be constrained by the technical challenges of estimating tropical vegetation carbon stocks. The research has shown that remotely sensed data can be used to estimate vegetation carbon stocks in a developing country such as Ghana and will continue to improve in response to the policy needs and signals. The major strength of this approach is that, it offers the opportunity for carbon stock estimates to be used to model emissions in the past, present and the future. The approach can also be used to assess and estimate land-use/land cover changes due to deforestation.

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