BIOMASS AND CARBON STORAGE OF A TROPICAL MONTANE RAIN FOREST ECOSYSTEM IN NORTHERN TANZANIA

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ABSTRACT

Field measures of tree dimensions and chemical soil analysis for organic carbon were used to quantify and estimate the biomass and carbon storage potential of a tropical montane rain forest ecosystem in Kilimanjaro, northern Tanzania. Permanent sample plots measuring 20m x 20m were established in six different sites in the forest and all trees > 6cm DBH enumerated. Samples from thirty trees representative of the forest were weighed in the laboratory for biomass determination. The sample tree data were used to develop biomass equations as a function of diameter at breast height (DBH). Carbon content was computed as 49% of the biomass for each site. Soil organic carbon was obtained by laboratory analysis of soil samples taken at different depths of a soil profile dug at each plot centre. The developed biomass equations and the soil organic carbon were used to estimate the biomass and carbon storage per hectare for the forest. The soil carbon storage was significantly higher than that in tree biomass: the aboveground and root carbon of trees averaged 17.64 tons/ha, while the soil carbon averaged 1424 tons/ha. The decrease of soil carbon with depth results from the greater accumulation of organic matter in the surface horizons. The higher carbon content of the soil is attributed to large quantities of organic matter resulting from leaf fall. The high density of small roots in the soil may also be a factor. The potential of this ecosystem to act as a carbon sink and mitigate greenhouse gas emissions is evident.

Key words: Biomass, Biomass Equations, Carbon Pools, and Montane Rain Forest.

INTRODUCTION

The missing carbon problem observed in the 1970s is still unresolved and at least 10% of the carbon dioxide added to the atmosphere by burning fossil fuels is unaccounted for (Broecker *et. al.*, 1979; Quay *et. al.*, 1992; Botkin *et. al.*, 1993; Lal *et. al.*, 1995; Washington and Mitchell, 1984; Manabe and Wetherald 1987; Hansen *et. al.*, 1984; Schlesinger and Thao, 1989; Schneider, 1990; IPCC, 1990; Mendelson and Rosenberg, 1994; Fredrick and Rosenberg, 1994; Koluchugna, 1995; Flavin and Tunali, 1996). Determining the amount and monitoring changes in vegetation biomass and carbon storage potential are important for understanding and balancing the global carbon budget and for analysing the fate of carbon dioxide produced by the burning of fossil fuels.

The 1990 national green house gas inventory of sources and sinks in Tanzania (CEEST, 1994; Omujuni, 1994) identified land use changes in particular agricultural practices and forestry as the most important sources and sinks of anthropogenic carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Currently, the necessary data to justify and quantify the sources and sinks of anthropogenic green house gases in Tanzania (and the world) are still inadequate, but that notwithstanding, mitigation plans have to be formulated. The lack of data poses a major setback in shaping out mitigation options for green house gas emissions in Tanzania's contribution to global environmental conservation. A comprehensive analysis of the potential of the major ecosystems to sequester carbon will enable us understand whether the corrective measures we take in terms of land use changes are likely to create net carbon sources or sinks and is fundamental in quantifying pathways for ecosystem carbon fluxes and sequestration. This information has important implications on efforts to mitigate global warming.

There are four known principle pools of global carbon, i.e. oceans, atmosphere, terrestrial ecosystems, and geological formations containing fossil and mineral carbon (Lal *et. al.*, 1995). The two known sinks for carbon include increase in atmospheric CO_2 concentration accounting for 3.2 Pg (3.2×10^9 tons) of carbon per year and absorption by oceans accounting for 2.0 Pg (2×10^9 tons) per year. The remaining part of 1.8 Pg. (1.8×10^9 tons) is believed to be absorbed by terrestrial ecosystems.

There appear to be only two uptakes of this missing carbon; i.e., biological uptake in the ocean, and in forest ecosystems (Botkin and Simpson, 1990; Mendelson and Rosenberg, 1994). There is however an unresolved controversy today as to whether terrestrial ecosystems are releasing carbon or withdrawing it from the atmosphere and accumulating it in vegetation and soils. Recent papers argue that the missing carbon is absorbed by terrestrial ecosystems (Lal *et al.,* 1995), especially forest vegetation (Broecker *et. al*., 1979; Speth, 1989; Tan *et al.*, 1990; Kaupi *et al.*, 1992; Quay, 1992; Brown *et al.*, 1993; Dixon *et. al*., 1994; Dixon, 1996). Previous analyses have suggested that land vegetation contain as much carbon as present in the atmosphere (Bolin *et al.*, 1979; Moore and Bolin, 1987). Furthermore, as much as 10% of the atmospheric carbon dioxide could be taken up and released annually by vegetation. Others suggest that terrestrial vegetation must be a source of carbon because deforestation proceeds faster than forest re-growth (Woodwell *et al.*, 1978; Houghton *et al.*, 1983; Houghton *et al.*, 1987; Melilo *et al.*, 1988).

Based on land use changes, a direct analysis has shown terrestrial ecosystems to be releasing carbon to the atmosphere (Houghton *et al,* 1983; Houghton, 1995). On the other hand, indirect estimates have shown terrestrial ecosystems to be accumulating albeit small amounts of carbon. It is however understood that terrestrial ecosystems have released carbon over the last century or so, and this controversy pertains to the last two or three decades (Houghton, 1995).

Three methods are used to determine the rate of biomass and carbon change in forest ecosystems (Boden *et al.*, 1990; Botkin *et al.,* 1993). (i) global monitoring of forest biomass so that net changes are observed over time, (ii) global monitoring of leaf biomass in forests and methods of examining net annual photosynthesis, and (iii) an indirect method of examining the annual oscillations of carbon dioxide concentrations in the atmosphere. To each of the first two methods, the soil carbon pool is an essential component to be assessed.

This study used direct field measurements of trees, and soil carbon to assess, and quantify the biomass and carbon storage potential of a tropical montane rain forest ecosystem in Kilimanjaro, northern Tanzania.

MATERIALS AND METHODS

Physical Environment of the Study Site

The natural forest on Mount Kilimanjaro is a tropical montane rain forest in northern Tanzania growing on one of the volcanic mountains; the third highest mountain in the world. The climax vegetation of the Kilimanjaro Forest Reserve between 1500 m - 3000m is a montane rain forest that varies in composition and structure along altitudinal and rainfall gradients. The upper eastern slopes are dominated by *Ocotea usambaresis*, *Hagenia abyssinica*, *Ilex mitis*, and *Podocarpus usambarensis*, sometimes grading into *Cassipourea malossana* and *Myrca salicifolia* down-slope and to the drier north (Lamprey *et. al.*, 1991). At lower altitudes *Newtonia buchanani*, *Macaranga kilimandscharica* and *Parinari excelsa* are common while at the 1200m level woody species are characterized by *Albizia spp.*, *Bombax schulmanianum, Chlorophora excelsa, Dyospiros melspiliformis, Khaya nyasica, Newtonia paucijuga*, and *Terminalia kilimandscharica*. The drier northwestern slopes are dominated by *Juniperus procera, Olea kilimandscharica , Podocarpus spp., Agauria salicifolia, Olea africana*, and *Olea welwitschii* at all levels (Lamprey et al 1991; Mwasaga, 1991). Tree species characteristic of the southern side include *Xymalos monospora, Conopharyngia usambarensis, Macaranga kilimandscharica,* and *Hagenia abyssinica* (Mwasaga, 1991)

The area has two rain seasons and two dry seasons. Long rains normally occur between March and May, while the short rains occur between November and December. The short rains are more pronounced at higher elevations. The dry season occurs between July and October and between January and February.

The Kilimanjaro soils are very varied most of them having been derived from volcanic rocks (Misana, 1991). The soils in the study area stretching from Mweka in Kibosho to Mrawi in Uru have been described as Mrawi *series* (Anderson, 1982). The soils are derived from the *Kibo Neogene Volcanics*. These rocks are composed dominantly of phonolites and trachytes which are basic in nature and range from trachy-andesite through trachyte to nepheline-rich phonolite (Downie and Wilkinson, 1972). Msanya and Maliondo (1999) described and characterised the soils of the study area. Table 1 presents the important characteristics of some soil profiles in the study area. The soils are acid, humic, moderately deep, friable to very friable, dark brown to very dark greyish brown sandy loams (in some places sandy clay loams) with weak to moderate structure.

Aboveground Vegetation Sampling

Permanent sample plots measuring 20m x 20m were established in six sites in the forest; there were two plots per site. The diameter at breast height (DBH) (1.3 m above the ground), total height and species were recorded for all trees with DBH > 6cm in each plot. Thirty trees of different species (representative of the forest) were selected and measured for laboratory analysis of biomass and carbon ratio.

Table 1: Analytical data of composite surface samples of some soil profiles in the study area

Soil profile		MWP1 – Mweka-Ngomberi plot 2	MWP2 - Mweka - Ngomberi 50m below junction to KINAPA forest	MWP3 -Mweka-Ngomberi Eucalyptus plot	MWP4 Mweka-Ngomberi Farm of Mr. August Ndakidemi	MWP5 - Mweka-Kifura Plot 5
Clay %		22	22	18	14	34
Silt %		24	28	24	20	12
Sand %		54	50	58	66	54
Texture class		SL	SL	SL	SL	SCL
Silt/clay ratio		1.09	1.27	1.33	1.43	0.35
Bulk density g/cc		1.3	1.4	1.6	1.5	1.5
pH H_2O		4.28	4.47	4.83	5.31	3.79
pH KCl		4.08	4.22	4.32	4.61	3.54
Organic C %		16.72	15.54	13.39	9.66	20.44
Total N %		0.89	1.20	0.83	0.09	0.18
C/N ratio		19	13	16	107	114
Available P mg/kg		3.65	3.94	3.94	4.23	4.84
CEC NH_4 OAc cmol(+)/kg		3.07	1.88	4.78	8.84	7.11
Exch. Ca cmol(+)/kg		0.50	0.30	1.20	3.00	1.30
Exch. Mg cmol(+)/kg		0.30	0.20	0.40	0.80	0.50
Exch. K cmol(+)/kg		0.04	0.04	0.4	0.15	0.13
Exch. Na cmol(+)/kg		0.08	0.06	0.08	0.03	0.06
TEB cmol(+)/kg		0.92	0.60	1.72	3.98	1.99
Base saturation %		30	32	36	45	28
Soil type	FAO-UNESCO	*Humic Cambisol (CMu)*	*Ferralic Cambisol (CMo)*	*Ferralic Cambisol (CMo)*	*Humic Cambisol (CMu)*	*Humic Cambisol (CMu)*
	USDA Soil Taxonomy	*Typic Haplumbrept*	*Psammentic Haplumbrept*	*Psammentic Haplumbrept*	*Psammentic Haplumbrept*	*Typic Haplumbrept*

Source: Msanya and Maliondo (1999)

The trees were measured for DBH, felled as close to the ground as possible, stems (+ branches) trimmed and cross cut into billets of 1-2m length (dimensions depended on weighing convenience) and separated into stems, branches, and leaves/twigs/small branches. All components for each tree were weighed for green weight. From each stem and branch two discs 2cm thickness were cross cut (about 0.5m from the base of stem/one of the branches). The discs were used for laboratory analysis of biomass and carbon ratio. A known amount of leaves and twigs were collected, weighed in the field then a sub sample taken to the laboratory.

Mineral Soil Sampling

At every plot centre a soil pit 1m by 2m was excavated to the rooting depth (hard layer). Based on colour changes, soil horizons were delineated and soil samples collected from each horizon. Core samples for bulk density and moisture content were taken from the top middle and bottom layers of the soil profile using steel core cylinders. Soil samples taken from different depths were sent to the laboratory for organic carbon analysis.

Forest Floor Sampling

Three open iron boxes, each measuring 20cm by 20cm surface area and a depth of 10 cm, were used to sample the L and F layer at three points from each plot. Three 15cm by 15cm boxes with a depth of 10cm were used to sample the H layer by gently pushing the boxes into the soil. The material collected from each layer was weighed, placed in polythene bags and sent to the laboratory where they were weighed, oven dried at 105^0C and re-weighed. Fine roots (2 mm diameter) in the organic soils (L, F, and H layers) were separated manually and gently adhering mineral soil washed off by tap water then weighed fresh, oven dried at 105^0C and re-weighed.

Soil Chemical Analysis

For moisture content determination, soil samples were weighed and then oven dried at 105^0C in the laboratory. Fresh mineral soil was sieved through 2mm screen. The soil samples were dried, grounded and sieved using a 2 mm sieve.

A known weight of the organic samples (L, F, & H) were ignited at 450^0C for 6 hours and re-weighed to determine the loss on ignition. Organic carbon content in the mineral soil was determined using the Black and Walkley method (Nelson and Sommers, 1982).

Data Analysis

Vegetation analysis

In the laboratory the stem and branch discs were cut into small samples of 2cm x 2cm, soaked in water for one week and weighed for green weight. They were then oven dried at $103^oC \pm 2^oC$ to a constant weight, to obtain the dry weight. The biomass ratio was computed as the ratio of the oven dry weight to the green weight for each tree stem, branches, and leaves/twigs. Biomass equations using the diameter (DBH) and height as predictor variables were developed for each component (Satoo and Madgwick, 1982; Stromgaard, 1986;

Marklund, 1988; Botkin and Simpson, 1990; Malimbwi et. al., 1992). These equations were used to predict biomass density and carbon storage (t/ha) by above ground vegetation using plot tree diameter data. The amount of carbon was taken as 49% of the biomass computed from the allometric models (Colman and Cote, 1968; Heygreen and Bowler, 1989; Jackson, IV 1992).

Calculations of organic carbon content

The oven dry weight of the LF layer was converted to a hectare basis by dividing by the area of the sampling frame used to sample the soil. For the H and mineral soil samples bulk density was calculated and multiplied by the organic carbon content in each soil layer and converted into aerial basis.

RESULTS

The study was conducted in the forest area just above the altitudinal limit for agriculture, covering the two-mile buffer zone separating the village from the forest reserve. Two plots were located in the village farmland and two in the buffer zone. The rest were located in the forest. The forest reserve was, however, extensively exploited for timber during 1970-80s, and former skid trails made by crawlers extracting logs are now big erosion gullies. As such there is no primary forest left, but secondary vegetation.

Table 2 show the prediction models developed to estimate the biomass of the montane rain forest ecosystem. Table 3 shows the tree species used in the development of the biomass models. The estimates were done independently using respective models for each parameter to avoid cumulative errors that could result from estimating a parameter from an estimate of another parameter. Table 4 shows that the total biomass predicted from the separate tree component models, was lowere than that predicted by the total biomass model. The above ground biomass of trees >6 cm DBH computed using these models for the different sites and different tree parts in the forest averaged 35 t/ha (Table 4). The carbon content of each part of the tree was taken as 49% of the biomass obtained using the models (Colman and Cote, 1968; Heygreen and Bowler, 1989; Jackson, IV 1992). The resulting above ground and root carbon content of trees >10 cm DBH in the montane rain forest (Kilimanjaro Forest Reserve) averaged 21.17 t/ha (Table 5). The soil carbon contents averaged 1498 t/ha (Table 5, Fig. 1). The variations in soil carbon with depth in the different soil profiles is shown in Figure 2. In general there is a decrease in organic carbon content of the soil with increasing depth from the surface. The soil organic carbon (soil carbon) is significantly high compared to amount of carbon contained in vegetation (tree) biomass.

Table 2. Biomass models for various parts of trees in a montane rain forest ecosystem northern Tanzania

Dependent variable	Model	r^2	SE	P
Total Biomass (above ground)	InTOTBIOM = -1.76 + 2.21lnDBH	0.81	0.215	<0.005
Stem Biomass	InSTBIOM = -2.47 + 2.31InDBH	0.79	0.236	<0.005
Branch Biomass	InBRBIOM = -2.14 + 1.86InDBH	0.63	0.284	<0.005
Leaf Biomass	InLFBIOM = -3.71 + 1.65InDBH	0.61	0.260	<0.005

Model: Inx = a + bInDBH
Where: x = biomass content (kg/tons)
DBH = Breast Height Diameter (1.3m above the ground)

Table 3. Sample tree used for development of biomass and carbon prediction models

Species	Family
Albizia gummifera	Mimosaceae
Aphloia theaeformis	Flacouriticiaceae
Cassipourea malosana	Olacaceae
Ilex mitis	
Macaranga capense	Euphorbiaceae
Maesa lanceolata	Myristicaceae
Makhamia platycalyx	
Musaenda microdonta	
Nuxia congesta	Loganiaceae
Ocotea usambarensis	Lauraceae
Olinia usambarensis	
Pauridiantha paucinervis	Rubiaceae
Polycias fulva	Araliaceae
Rapanaea rhododendroides	Mysticaceae
Syzygium guineense	Myritaceae
Vangueria sp.	Rubiaceae
Vernonia sp.	Compositae

Table 4. Above ground biomass (t/ha) in a Montane Rain Forest Ecosystem Northern Tanzania

Site #	LF-B	ST-B	BR-B	RT-B	TT-B
1	0.072	15.08	5.80	12.13	52.72
2	0.069	19.48	6.06	14.88	64.68
3	0.005	0.47	0.33	0.43	1.89
4	0.069	12.92	5.40	10.60	46.10
5	0.072	14.27	5.78	11.65	50.65
Mean	0.057	12.44	4.67	9.94	43.21
% Total	0.210	46.00	17.30	36.80	

LF-B = Leaf Biomass ST-B = Stem Biomass BR-B = Branch Biomass
RT-B = Root Biomass TT-B = Total Tree Biomass

Table 5. Tree and Soil Carbon Storage (t/ha) in a Montane Rain Forest Ecosystem Northern Tanzania

Site #	LF-C	ST-C	BR-C	RT-C	TT-C	SOIL-C	TOT-C
1	0.035	7.39	2.84	5.94	25.83	1823.60	1849.40
2	0.034	9.55	2.97	7.29	31.69	1085.70	1117.39
3	0.003	0.23	0.16	0.21	0.93	1041.90	1042.83
4	0.033	6.33	2.65	5.19	22.59	1743.60	1766.19
5	0.035	6.99	2.83	5.71	24.82	1793.80	1834. 18
Mean	0.028	6.09	2.29	4.87	21.17	1497.70	1521.99
% Total	0.002	0.04	0.15	0.03	1.4	98.4	

LF-C = Leaf Carbon ST-C = Stem Carbon BR-C = Branch Carbon RT-C = Root Carbon TT-C = Total Tree Carbon SOIL-C = Soil Carbon TOT-C = Ecosystem Carbon

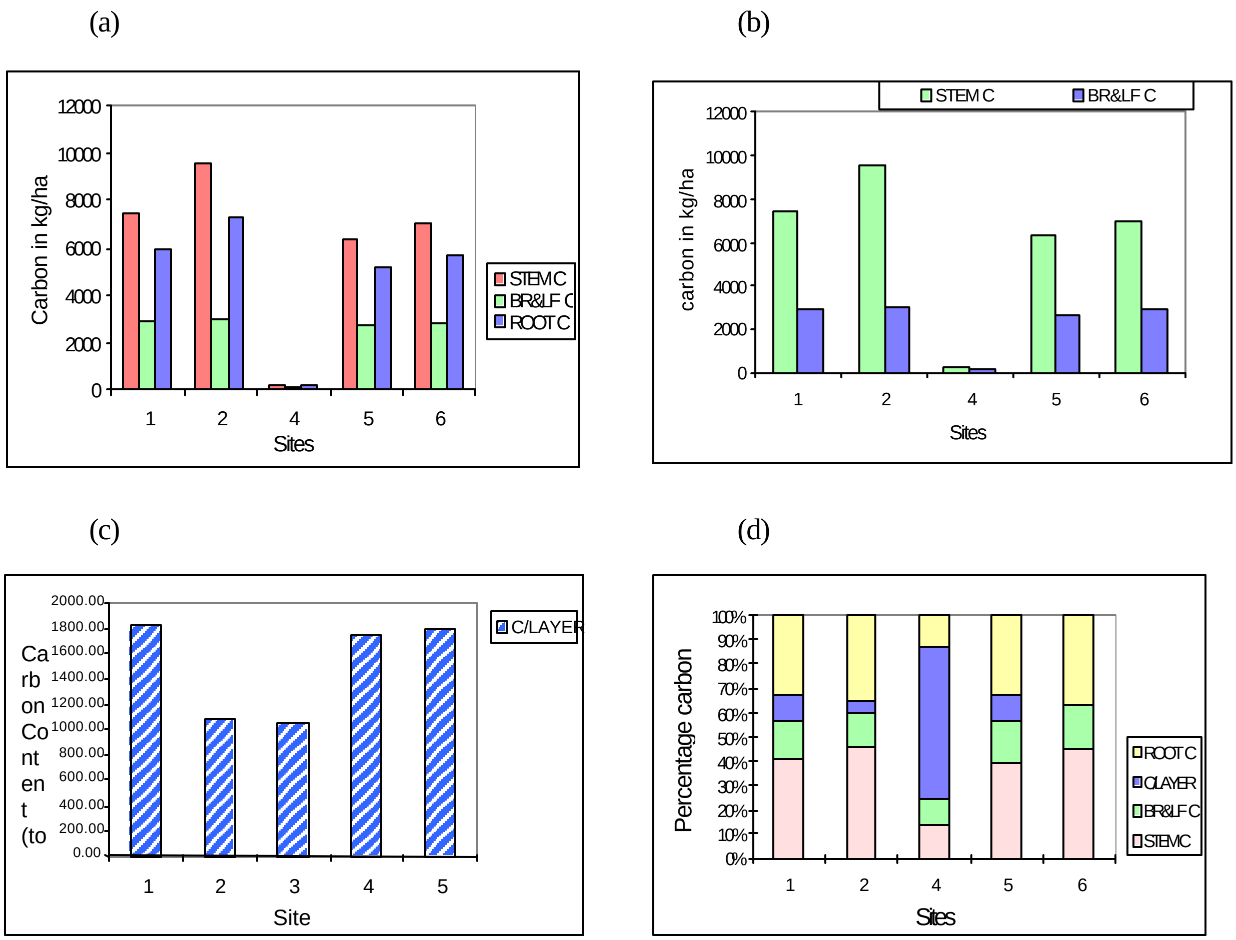

Figure 1. **Tree and soil carbon content in a montane rain forest northern Tanzania. (a) carbon content in the different tree parts (b) above ground tree carbon content (c) soil carbon content (d) percentage carbon content in the soil and different tree parts. Soil carbon is expressed in tons/ha while tree carbon is expressed in kg/ha. Soil carbon pools seem to be significantly high compared to tree carbon. (STEMC = stem carbon, ROOTC = root carbon, BR&LFC = branch and leaf carbon, C/LAYER = soil carbon).**

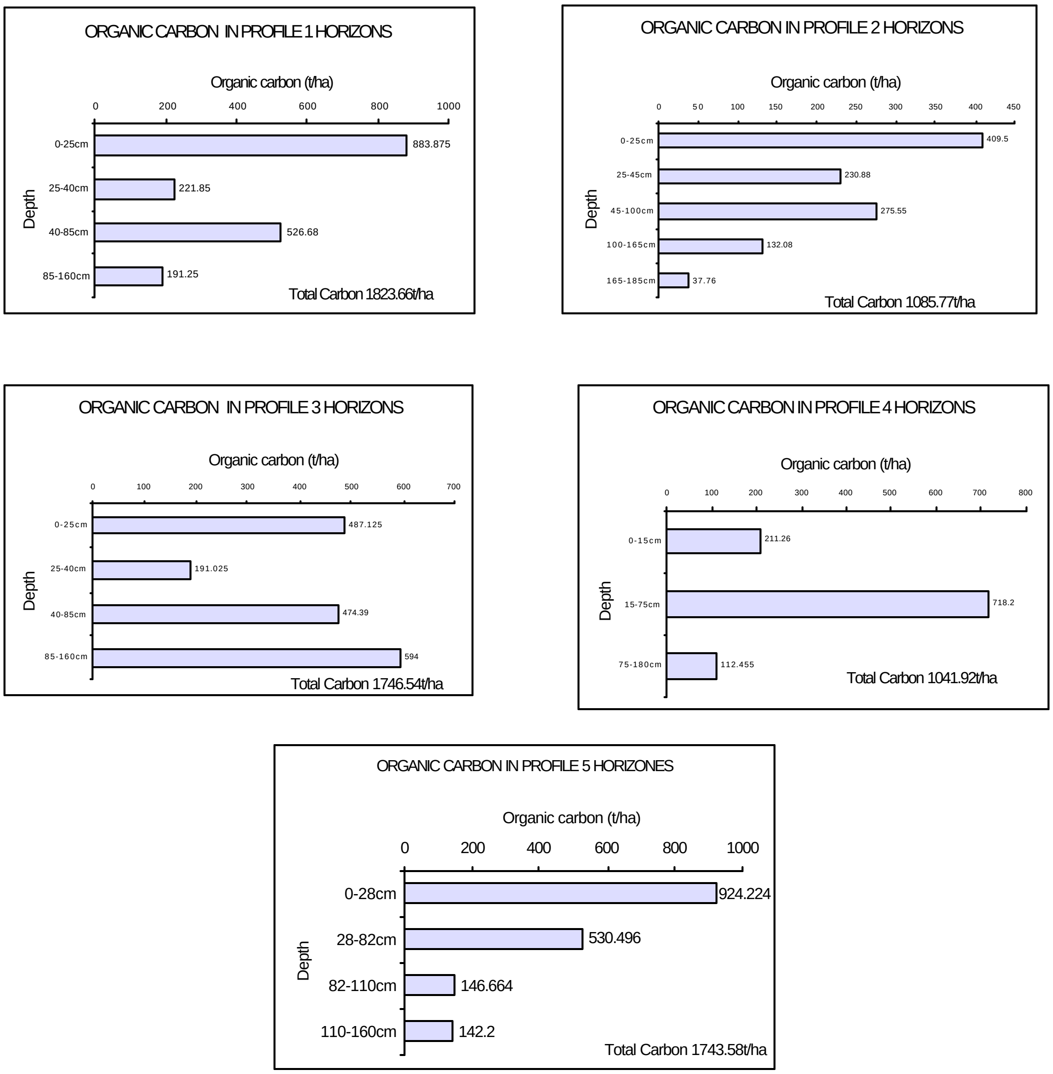

Figure 2. **Variations in organic carbon with profile depth in the different profile horizons at different sites in a montane rain forest ecosystem northern Tanzania. The amount of organic carbon seem to decrease with increasing depth from the soil surface**

DISCUSSION

We believe that our estimates of carbon storage of the montane rain forest are the first of this nature in Eastern Africa that consider both vegetation and soil potential to accumulate carbon. Most studies considered only the above ground components of a forest ecosystem (stems, branches and leaves). As observed in this study there is an enormous amount of carbon stored in the soil component of a forest ecosystem compared to the vegetative part. However we believe that the amount of carbon in the above ground parts could be higher by including the undergrowth layer, and saplings or trees with DBH below 6cm which are relatively numerous in some parts of the forest. In this study, only trees with DBH greater or equal to 6cm were considered.

A comparison with other tropical rainforests indicates that this forest has a very low total biomass, with 35 t/ha in aboveground and 9.9 t/ha below-ground biomass. In a tropical montane rain forest in Papua New Guinea, Edwards and Grubb (1977) reported 295 and 40 t/ha, for above- and below-ground biomass, respectively. Brown *et al.* (1995) reported an estimate of 162 - 285 t/ha, as the above-ground biomass for forests of tropical America/Brazilian Amazon, with root biomass accounting for 30% of the total biomass.
Edwards and Grubb (1977) summarised data from other tropical forests with 142 - 310t/ha and 40-72 t/ha as above-ground biomass for lower montane forests. The summarised data also showed that lowland tropical rain forests had higher above ground biomass than montane forests, but the latter had higher organic matter in the soil than held in the former. Lundgren (1978) reported above-ground biomass of 450 t/ha and below ground biomass of 37.3 t/hafor Mazumbai natural forest, an intermediate montane raiforests in Tanzania.

This low biomass values for Kilimanjaro montane forest indicates it is highly degraded. The forest has been, and is still under a sustained pressure due to illegal extraction of valuable timber such as *Ocotea usambarensis* and *Podocarpus spp*. As these large trees (DBH >60cm) are removed, they leave large gaps that support pioneer tree species, shrubs and herbs; secondary pioneer tree species such as *Macaranga capense* and *Polycias fulva* dominate the canopy. Harvesting for other tree products such as poles is also taking place.

The above results also indicate that we are dealing with a very fragile ecosystem. The reduced vegetation cover, and the steep slopes characterising the forest, means that it is very susceptible to soil erosion, if more vegetation is removed. Increased removal of vegetation, either for agriculture or timber harvesting, will further expose the forest floor and soil organic matter to accelerated decomposition, resulting in higher emission of CO2 and other greenhouse gases that lead to global warming. Uncontrolled fires, which are becoming increasingly common in this ecosystem, will further destroy the forest floor as well as the vegetation, and hence increase the emission of greenhouse gases and other gases such NO_x which destroy the ozone layer.

The amount of C contained in the soil (1498 t/ha), representing about 98% of the site C, compares favourably with the 6000t/ha (soil OM = 1200t/ha) reported by Edwards and Grubb (1977) in a montane rainforest in Papua New Guinea. Values from the present study are also much higher than 247 t/ha reported for the Mazumbai rainforest in Tanzania (Lundgren, 1978). Our study included C in the forest floor and fine roots within the forest floor which was not accounted in the other two studies (Edwards and Grubb, 1977; Lundgren, 1978).

The higher soil C content in the current study is attributed to deep rooting depth with decomposing roots contributing to soil C, and thick forest floor due to accumulation of litter and logging residue. As the productivity and resilience of the soil is mainly governed by its organic matter status (i.e. nutrient reservoir, buffering capacity, and water holding capacity, detoxification of pollutants), this important pool must protected.

CONCLUSION

There is an increasing pressure from the surrounding villages, having serious land shortage due to overpopulation, and low land productivity caused by poor land husbandry, to degazette part of the forest and raise agricultural crops such as coffee and bananas. However, it should be evident from the above results that if this forest, growing on steep slopes, is cleared for agriculture, the land will be productive only for a very short period before being impoverished through the loss of the topsoil soil by accelerated erosion. Assuming that the land will then be abandoned, it will take many years before it reaches the original climax vegetation. It thus appears that this land should be left as forest with controlled harvesting of non-wood forest products, and selective logging of old timber species.

REFERENCES

Anderson, G.D. (1982). The soils and land use potential of the southern and eastern slopes of Kilimanjaro. Resource Management Paper No. 1. Institute of Resource Assessment, University of Dar es Salaam, Tanzania; and International Development Program, Clark University, USA. 211 pp.

Bolin, B. (1977). Changes in land biota and their importance in the carbon cycle. *Science 196:613-615.*

Bolin, B. Degens, E. T. Duvigneaud, P. Kempe, S. (1979). The global biogeochemical carbon cycle.*In* Bolin, B. Degens, E. T. Kempe, S. A. and Ketner P. (eds.). The Global Carbon Cycle *John Willey & Sons New York Pp.1-56.*

Botkin D. B. Simpson, G. L. (1990). Biomass of the North America Boreal Forests. A step towards accurate global measures. *Biogeochemistry 9:161-174.*

Botkin, D. B. Simpson, G. L. Nisbet, A. R. (1993). Biomass and carbon storage of the North Americandeciduous forests. *Biogeochemistry 20:1-17.*

Brocker, W.S. Takahashi, T. Simpson, H. J. and Peng, T. H. (1979). Fate of fossil fuel carbon dioxide and the global carbon budget. *Science 206:409-418.*

Boden, T. A. Kanciruk, P. Farrel, M. P. (eds.) (1990). Trends ‘90’. A compendium of data on global change. *Oak Ridge Nat. Lab. Oak Ridge TN.*

Brown, F., Martinelli, L.A., Thomas, W.W., Moreira, M.Z., Cid ferreira, C.A., and victoia, R.A. (1995) Uncertainity in the biomass of Amazonian forests: An example from Randonia, Brazil. *Forest Ecology and Management* 75:175-189.

Brown, S. Hall, C. A. S. Knabe, W. Raich, J. Trexler, M.C. Woomer, P. (1993). Tropical Forests: their past, present, and potential future role in the terrestrial carbon budget. *Water, Air and Soil Pollution 70: 71-94.*

CEEST. (1994). Sources and sinks of green house gases in Tanzania for 1990. *Report # 5/1994. CEEST, Dar-es-Salaam.*

Detwiler, R. P. and Hall, C.A.S. (1988). Tropical forests and the global carbon cycle. *Science 23: 42-47.*

Dixon, R. K. Andrasco, K. J. Sussman, F. A. Lavinson, M. A. Trexler, M. C. Vinson, T. S. (1993). Forests sector carbon off set programs: near term opportunities to reduce green house gas emissions to the atmosphere. *Water, Air and Soil Pollution 70: 561- 577.*

Dixon, R. K. Brown, S. Houghton, R. A. Solomon, A. M. Trexler, M. C. Wisniewski, J. 1994a. Carbon pools and flux of global forest ecosystems. *Science 263:185-190*.

Dixon, R. K. Winjum, J. K. Andrasko, K. J. Lee, J. J. Schroeder, P. E. (1994b). Integrated systems: assessment of promising agroforestry and alternative land use practices to enhance carbon conservation and sequestration. *Climate Change 30:1-23.*

Dixon, R. K. (1996). Agroforestry systems and green house gases. Agroforestry *Today Vol. 8 # 1: 11-14.*

Downie, C. Wilkinson, P. (1972). The geology of Kilimanjaro. Department of Geology, University of Sheffield, and the Geological Survey of Tanzania. University of Sheffield Press. 253 pp.

Edwards, P.J. and Grubb, P.J. (1977). Studies of mineral cyling in a montane forest in New Guinea: 1. Thedistribution of organic matter in the vegetation and soil.. *Journal of Ecology 65:943-960*.

Flavin, C. Tunali, O. (1996). *In* Peterson A.J. (ed.) Climate of hope. New strategies for stabilising the world's atmosphere. *World Watch Paper 130. 84pp*.

Fredrick, K.D. Rosenberg, J.N. (eds.) (1994). Assessing the impact of climate change on natural resource systems.

Hall, J. B. (1991). Multiple-nearest-tree sampling in an ecological survey of Afromontane catchment forest. *Forest Ecology & Management 42:245-265*.

Hobbs, J.A. Brown, P. L. (1965). Effect of cropping and management on nitrogen and organic carbon content of western Kansas soils. *Kansas Agricultural Experiment Station Technical Bulletin 144pp.*

Houghton, R.A. (1995). Changes in the storage of terrestrial carbon since 1950. *In R. Lal, J. Kimble, E. Levine, Stewart (eds.) Soil Management and Greenhouse Effect. CRC Press Inc. Pp* .45-65.

Houghton, R. A. Hobbie, J.E. Melillo, J.M. Moore, B. Peterson B.J. Shaver G.R. & Woodwell, G. M. (1983). Changes in the carbon content of terrestrial biota and soils between 1860 and 1980. A net release carbon dioxide to the atmosphere. *Ecological Monographs 53: 235-262.*

Houghton, R. A. Boone, R. D. Fruci, J.R. Hobbie, J.E. Melillo, J.M Palm, C. A. Peterson, B.J. Shaver, G. R. Woodwell, G. M. Moore, B. Skole, D.L. & Myers, N. (1987). The flux of carbon from terrestrial ecosystems to the atmosphere in 1980 due to changes in land use: geographic distribution of the global flux. *Tellus 39B:122-139.*

Intergovernmental Program for Climate Change (IPCC) (1990). Houghton, J. T. Jeckins, G. J. and Epgraums, J.J. (eds.) Climate Change; the IPCC Scientific Assessment Working Group I Report . *WMD and UNEP Cambridge University Press 365pp.*

Lamprey, R. H., Michelmore, F. Lamprey, F. H. (1991). Changes in the boundary of the montane rainforest on Mount Kilimanjaro between 1958 and 1987. *In* Newmark, William D. (ed.) *The Conservation of* Mount Kilimanjaro, IUCN, Gland Switzerland and Cambridge UK.136pp.

Kobak, K.I. Kondrashover, N. Yu. (1987). Anthopogenic impact on soil carbon reservoir and carbon cycle. *Meteorological Hydrology 5:39-46.*

Kolchugina, T.P., Vinson, T.S.; Gostan, G.G.; Rochleou, V.A. and Schlentiner , S.F. (1995). Carbon pools,fluxes and sequestration potential in soils of the former Soviet Union. *In R. Lal J. Kimble, E. Levine, B.A. Stewart (eds.) Soil Management and Greenhouse Effect. CRC Press Inc. Pp. 25-40.*

Lal, R. Fausey, N. R. Ecket, D. J. (1995). Land use and soil management effects on emmissions of radioactively active gases from two soils in Ohio. *In R. Lal, J. Kimble, E. Levine, B.A Stewart (eds.) Soil management and green house effect. CRC Press Inc. 41-59.*

Lovett, J. C. (1996). Elevation and latitudinal changes in tree associations and diversity in the eastern arc mountains of Tanzania. *J. Trop. Ecol.12:245-265.*

Lundgren, B.(1978). Soil condition and nutrient cycling under natural and plantation forest in Tanzania Highlands. *Report in Forest Ecology and Forest Soil 31 Uppsala. 426* ***p***.

Malimbwi, R. E. Solberg, B. Luoga, E.J. (1994). Estimation of biomass and volume in miombo woodlands at Kitulangalo Forest Reserve Tanzania. *J. Trop. For. Sci. 7(2):230-242.*

Mann L.K.(1986). Changes in soil carbon storage after cultivation. *Soil Science 421:279 - 288.*

Marklund, L. G. (1988). Biomass functions for Pine, Spruce, and Birch in Sweden. *Department of Forest Survey, Report # 45 Swedish University of Agric Sciences Umea 1988).*

Melillo, J.M. Fruci, J.R. Houghton, R. A. Moore, B.III & Skole, D.L. (1988). Land use change in the Soviet Union between 1850 and 1980. Causes of net release of CO_2 to the atmosphere: *Tellus 40B:116-128.*

Mendelson, R. Rosenberg, J. N. (1994). Framework for integrated assessment of global warming impacts. *Climate Change 28:15-44.*

Misana, B.S. (1991). The importance of Mount Kilimanjaro and the need for its integrated management and conservation. *In* Newmark, William D. (ed.) *The Conservation of Mount Kilimanjaro, IUCN, Gland Switzerland and Cambridge UK. 136pp.*

Moore, III B & Bolin, B. (1987). The Oceans Carbon Dioxide and Global Climate Change.*Oceanus 29: 9-15.*

Msanya, B.M. Maliondo, S.M. (1999). Soil characterisation in the area within and around the KilimanjaroRain Forest. Draft report, Department of Forest Biology- Faculty of Forestry and Nature Conservation and Department of Soil Science- Faculty of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania.

Mwasaga, B. C. (1991). The Natural Forests of Mount Kilimanjaro. *In* Newmark, William D. (ed.) *The Conservation of Mount Kilimanjaro, IUCN, Gland Switzerland and Cambridge UK. 136pp.*

Nelson, D.W. and Sommers, L.E. (1982). Total carbon, organic carbon and organic matter. In: Methods of Soil Analysis, part 2, 2nd edit. (eds. A.L. Page, R.H. Miller and D.R. Keeney), PP. 539 -579. ASA, SSSA Monograph no. 9, Madison, Wisconsin.

Post, W. M. Peng T. H. Emanuel, W.R. King, A.W. Dale, V.H. De Angelis D.L. (1990). The global carbon cycle. *Am. Sci. 78:310-326* .

Satoo, T. Madgwick, I. A. H. (1982). Forest Biomass. *Martinus Nijhoff/Dr. W. Junk Publishers,Boston/London.*

Schlesinger, W.H. (1984). Soil organic matter: a source of atmospheric carbon dioxide. *In G. M. Woodwell (ed.) The role of terrestrial vegetation in the global carbon cycle measurement by remote sensing. SCOPE. John Wiley and Sons. New York.*

Schultz, D. D. & Co. Ltd. (1973). Indigenous forest inventory of five areas of the United Republic of Tanzania. *Vancouver, Canada.*

Schroeder, P.E. and Winjun, J.K. (1995). Assessing Brazil's carbon burget: 1. Biotic carbon pools. *Forest Ecology and Management* 75:77-86.

Speth, G. (1989). Can the world be saved? Pp. 289-302 in Ecological Economics. *Elsevier Science Publishers, B. V. Amsterdam, The Netherlands.*

Stromgard, P. (1986). Biomass equations reviewed. The example from Zambian miombo. *Institute of Geography, University of Copenhagen, Oster Voldgade 10, DK 1350 Copenhagen K, Denmark.*

Tan, P. P. Fung, I. Y. Takahashi, T. (1990). Observational constraints on the global atmospheric carbon dioxide budget. *Science 247:1431-1438.*

Temu, A. B. (1985). Inventory problems of tropical woodlands. Can multistage sampling be applied? *World Forest Management Pp. 117-181.*

Tiessen, J. Stewart, J.W.B. (1983). Particle size fractions and their use in studies of soils organic matter.Cultivation effect on organic matter decomposition in size fraction. *Soil Science Society of America Journal 47:509-514.*

Woodwell, G. M. Whitaker, R.H. Reiners, W. A. Likens, G. E. Hall, C. A. S. Delwiche C.C. Botkin, D. B. (1978). The biota and the world carbon budget. *Science 199:141-146.*