

THE POTENTIAL OF AFROMONTANE RAIN FORESTS TO MITIGATE CARBON EMISSIONS IN TANZANIA

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ABSTRACT

One of the major ways of mitigating carbon emissions is by emission avoidance or conserving existing carbon (C) pools on the land through slowing deforestation or improved forest harvesting practices. Field measures of tree dimensions and chemical soil analysis for organic carbon were used to quantify the carbon (C) storage potential of three tropical montane rain forest ecosystems; one on the slopes of Mount Kilimanjaro and two (Usambara and Uluguru) in the Eastern Arc Mountains of Tanzania. The above ground and root carbon of trees ranged from 295 ± 8 to $517 \pm 17 \text{ t h}^{-1}$. The tree carbon storage was lowest in the Kilimanjaro forest (295 ± 8 (SD) t h^{-1}), and highest in the Usambara forest (517 ± 17 (SD) t h^{-1}). The C storage in the Ulugurus was 388 ± 10 (SD) t h^{-1} . The soil carbon storage (1423.7 t h^{-1}) in Kilimanjaro was significantly higher than that in tree biomass. On the other hand the soil carbon (418 ± 100 and $295 \pm 53 \text{ t h}^{-1}$) in the Usambara and Uluguru respectively) was significantly lower than the biomass carbon in both forests in the Eastern Arc forests. The potential of these ecosystems to act as carbon sink and mitigate greenhouse gas emissions is evident. This capacity for carbon storage, population pressure and the extensiveness of these forests in the region makes their conservation of global significance for carbon emission mitigation.

Key words: Montane rain forest, carbon storage, emission mitigation, carbon pool.

INTRODUCTION

At the 1992 Rio conference on environment and sustainable development a non-legally binding statement of principles was adopted for the management, conservation and sustainable development of multiple use forests. The statement documents the importance of incorporating environmental costs and benefits into market mechanism to achieve the dual benefit of forest conservation and sustainable development both domestically and sustainably. The efforts to develop climate action plans within countries that have signed or are about to sign the International Framework Convention on Climate Change have caused a great attention to the value of improving trees and forests as one of the potential mitigation strategies.

Land use, Land use Changes and Forestry (LULUCF) activities have historically been and are currently net sources of carbon (as carbon dioxide) to the atmosphere (Brown *et al.*, 1996;

Sampson, 1993). On the other hand there is a potential for LULUCF activities to mitigate carbon emissions. This may be achieved through emission avoidance or conserving existing carbon (C) pools on the land (e.g. slowing deforestation or improved forest harvesting practices) and carbon sequestration or expanding carbon storage in forest ecosystems by increasing the area and/or carbon density of forests (e.g. in plantations, agroforests, natural regeneration, soil management). Others include increasing storage in durable wood products and substituting sustainably grown wood for energy intensive and cement based products (e.g. biofuels, construction materials) (Dixon *et al.*, 1994b; Sampson, 1995; Winjum *et al.*, 1997; Dixon, 1996; Brown *et al.*, 1996; Brown, 1997; 1999; Munishi, 2001).

Understanding the role of terrestrial ecosystems in the global carbon (C) cycle has become increasingly important as policy makers consider options to address the issues associated with

global climate change (Brown, 1997; Wayburn 2000; Wisniewski and Sampson, 1993). With the increasing concern about the rise in atmospheric carbon dioxide (CO₂) concentration and its implications for global climate, the role of tropical forest management in mitigating CO₂ emissions is receiving attention.

Biomass and carbon estimates for tropical forests are particularly needed as globally they are undergoing the greatest rates of change and reliable estimates are few (Brown, 1997). Their biomass and carbon content are high, thus influencing their role in the global C cycle. Tropical forests have the greatest potential for mitigating atmospheric CO₂ emissions through conservation and management (Brown *et al.*, 1996). Changes in the cover, use, and management of forests produce sources and sinks of CO₂ that is exchanged with the biosphere. Assessments of the magnitude of these sources and sinks require reliable estimates of the biomass density of forests and change over time (Brown, 1997).

An analysis of the potential of different ecosystems to sequester or store carbon is a key to understanding whether the corrective measures taken in land use changes and forest management are likely to create net carbon sources or sinks. Such assessments are also fundamental in quantifying pathways for ecosystem carbon fluxes and sequestration.

The present study assessed the potential of montane rain forest ecosystems in Tanzania to mitigate carbon emissions through biomass accumulation and soil carbon.

MATERIALS AND METHODS

Study sites

Data were collected from three montane forests, one on the slopes of Mount Kilimanjaro and two from the Eastern Arc Mountains. The natural forest on Mount Kilimanjaro is a tropical montane rain forest in northern Tanzania growing on one of the volcanic mountains. 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 usambarensis, *Hagenia abyssinica*, *Ilex mitis*, and *Podocarpus usambarensis*, sometimes grading into *Cassipourea mallossana* and *Myrcia salicifolia* down-slope and to the drier north. At lower altitudes *Newtonia buchananii*, *Macaranga kilimandscharica* and *Parinari excelsa* are common while at the 1200m level woody species are characterized by *Albizia spp.*, *Bombax schimmanianum*, *Milicia excelsa*, *Diospiros mespiliformis*, *Khaya anthotheca*, *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). Tree species characteristic of the southern side include *Xymalos monospora*, *Tabernaemontana usambarensis*, *Macaranga kilimandscharica*, and *Hagenia abyssinica*.

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

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*. The rocks are composed dominantly of phonolites and trachytes to nepheline-rich phonolite. The northern, western, and southern sides of the mountain are covered by deep fertile soils. 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 loam) with weak to moderate structure.

The west Usambara and Uluguru mountain ranges are part of the Eastern Arc Mountains of Tanzania. The West Usambara range is located in the northern part of the Eastern Arc Mountains (4° 25' – 5° 07' S and 38° 10' – 38° 35' E) and cover an area of about 2,200 km². The geology of the mountains is late Pre-Cambrian rocks of the Usagara System, metamorphic rocks of gneiss

type with two main highland soil types, the Humic Ferrisols in the drier areas and Humic Ferralitic soils in the more humid and wet areas (Hall 1980). The climate is oceanic with bimodal rainfall partly determined by their proximity to the Indian Ocean and the equator. Rainfall peaks in April and November. The mean annual rainfall maximum is 2,000 mm in the wettest areas, falling to less than 600 mm in the rain shadow areas. Moist forests occur in a wide elevation range covering extensive areas of the wetter eastern, southern, and northern sides of the mountains (van der Willigen and Lovett, 1979; Lovett, 1996).

In the west Usambaras, the study sites were the Mazumbai and Kisimagonja Forest Reserves (4° 50' S 38° 30' E), within an elevation range of 1,300 to 1,910 m. The monthly rainfall averages > 50 mm with mean annual rainfall of 1300 mm (Redhead, 1979; Hall, 1980; Munishi, 2001; Munishi, *et al.* in press.). The vegetation consists of lower montane to montane evergreen rain forests (Redhead, 1981; Hall, 1990; Munishi 2001) (Fig. 1).

The Uluguru Mountains (7°02' - 7°16' and 38° 0' - 38° 12') are located in the central part of the Eastern Arc Mountains. The Uluguru bedrock is made up of Precambrian metamorphic rocks dominated by hornblende-pyroxine granulites with injections of granite and gneiss and minor basic intrusions (Rapp *et al.*, 1972). The climate is oceanic with bimodal rainfall, peaking in April and November. The annual rainfall is 2,900 - 4,000 mm on the eastern windward slopes and 1,200 - 3,100 mm on the western leeward slopes. A pronounced dry season occurs on the western slopes, whereas the eastern slopes have more than 100 mm of rainfall every month (Lovett and Pócs 1993). In the Ulugurus, the study site was the Uluguru North Forest Reserve with lower montane, sub-montane, and montane evergreen rain forests (Lovett and Pócs, 1993) (Fig. 2).

Data collection

Permanent sample plots measuring 20m x 20m were established in six sites in the Kilimanjaro forest. The diameter at breast height (DBH) (1.3 m above the ground), total height and species were recorded for all trees with DBH > 10cm in each plot. Thirty trees of different species (representative of the forest) were selected and measured for laboratory analysis of biomass and

carbon ratio. 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 dried in the laboratory for oven dry weight.

A soil profile was dug at each plot centre and soil samples taken from different depths and samples then analysed for organic carbon in the laboratory.

Open iron boxes 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 10 cm were used to sample the H layer by gently drilling the boxes into the soil. The material collected from each layer was weighed and sent to the laboratory where they were weighed, oven dried at 105°C and re-weighed. Fine roots (2mm 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°C and re-weighed.

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. These were weighed and then oven dried at 105°C in the laboratory. The mineral soil was sieved through 2 mm screen.

In the eastern Arc Mountains one hundred 0.02 ha rectangular plots (20m x 10m) were established in each of the west Usambara and Uluguru forests. Due to close proximity, Mazumbai and Kisimagonja Forest Reserves in the west Usambaras were combined as one west Usambara site with 100 plots (Fig 1). Plots were established on line transects oriented along elevation gradients. Ten transects were

established in each forest with an average length of 1000 m (1 km) starting from the forest edge towards the ridge top to the highest point. Distance between transect lines were approximately 200m. Plots were laid with their long axis perpendicular to the direction of slope. The distance between plots along transects was approximately 100 m and the elevation difference between plots ranged from 5 m to 80 m. A plot that fell on a completely treeless site was established on a randomly selected nearby adjacent area with trees. All trees in each plot with diameter at breast height (dbh) ≥ 6 cm were identified and measured for diameter at breast height (dbh). One hundred and twenty (60 from each forest) sample trees of thirty different species (two from each species) were selected from every second plot site and measured for dbh using a caliper or diameter tape, and total height using a Suunto hypsometer. The sample trees were selected purposely to represent the most common tree species in these forests and needed not be within the plot but necessarily within the proximity of the respective plots. The two trees representing a species were also selected purposely from different sizes to take into account possible variations in individual tree density. Total height was defined as the height from the ground to 90% of the crown depth (length) (Phillip, 1994). Wood cores were extracted from these sample trees using an increment borer at approximately 1.3 m from the ground. The green weight, length, and diameter of each core were measured. Core diameter was an average of measurements from the two ends and the middle of the cores. The cores were oven dried at $103 \pm 2^\circ\text{C}$ to constant weight and used to compute basic density. Soil samples were collected from each plot at three points along the center-line (5m, 10m, and 15m) and at two different depths, 0-15cm and 15-30cm. The three samples from each depth were combined, air dried, and sieved to pass through a 0.2mm sieve. Another set of forty soil cores; twenty from each 0-15cm and 15-30cm depths were collected from selected areas of each forest at every fifth plot using bulk density core samplers and oven dried to constant weight for bulk density determination. The wood core volumes were computed as the product of their cross-sectional areas and lengths. Wood density was computed as core oven dry weight divided by core volume for each tree species. Soil bulk density was computed as the ratio of the soil oven dry weight to the soil core volume for each sample. Percent

soil C was determined using a CHN elemental analyzer, model NC2100, CE Instruments.

Data analysis

Vegetation analysis

In the laboratory the stem and branch discs from Kilimanjaro 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 $103^\circ\text{C} \pm 2^\circ\text{C}$ 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. The biomass ratio were used to compute the biomass of each sample tree. Biomass equations using the diameter (DBH) as predictor variable were developed for each component (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.

For the Eastern Arc data, tree volumes were computed as the product of the tree basal area and tree height adjusted for taper by the cone formula (Phillip, 1994) and averaged for each two trees representing a species. The dbhs and density of each of the two trees representing a species were averaged to give a species average dbh and density. The dbh was then regressed against tree volume to develop a volume prediction model that was used to compute tree volumes in each of the 100 plots. Tree biomass was computed as the product of the tree volume and the wood basic density (Malimbwi *et al.*, 2000). In computing tree biomasses different wood basic densities were used. These included either the specific species density for species with known densities in different plots not represented in the sample trees, family average for species that are different from the sample trees whose density was not known but belong to a family whose density is known, or sample tree average values for species belonging to the sample trees. Individual tree biomasses were aggregated to plot biomass and divided by the plot area to obtain biomass density (metric tons ha^{-1}). A biomass expansion factor (BEF) (Brown, 1997) of 29% was used to estimate the biomass of the branches and foliage based on estimates by Hall (1980). Root biomasses were based on estimates by Brown and Lugo (1992) of 22% in

tropical forests where they used data from various tropical regions, and Malimbwi *et al.*, (1994) who obtained similar figure for tropical dry forests in eastern Tanzania.

A common method of estimating tree biomass is to develop biomass models based on dbh and/or height by harvesting (felling) and weighing sample trees and tree components in the field (Brown *et al.*, 1989; Malimbwi *et al.*, 1994; 2000). This procedure requires much time and is sometimes costly. It was therefore not feasible in the present study due to time constraints and restrictions applicable to the catchment forests regarding tree harvesting and sampling. Rapid estimates using both field measurements, auxiliary information such as double sampling for sample tree volume prediction and biomass expansion factor obtained from studies in similar tropical forests is presented (Brown *et al.* 1989; Hall 1980). Double sampling estimate is a method of incorporating auxiliary information in estimates where a relationship derived from one sample is applied to another sample for estimates (Brown *et al.* 1989; Michelakackis and Cunia 1987). Example in this study, volume prediction model developed from the sample trees was used to estimate plot tree volumes and volume used to estimate biomass. The forests in this study are mature and are believed to be in dynamic equilibrium and our assessments are for potential carbon stocks. This method therefore gives at least first approximations for estimates of carbon storage potential of the forests. The percent soil C for each forest was computed as the average of the 100 plots in each depth.

Tree biomass was converted to C through multiplication by 0.49 (Colman and Cote, 1968; quoted in Haygreen and Bowler, 1989; Chidumuyo, 1993; Haygreen and Bowler, 1989; Jackson IV 1992; Malimbwi *et al.*, 1994; Brown 1997; Ford-Robertson *et al.*, 2000). Soil C density for each forest was computed as the product of volume of soil per unit area (1 ha), bulk density, and the average percent C for each depth. Biomass and carbon storage by different plant communities was also estimated using similar procedure as those used for the entire forests.

Soil chemical analysis

The soil samples from Kilimanjaro were dried, grounded and sieved using a 2mm sieve. A known weight of the organic samples (L, F, & H) were ignited at 450°C 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.

Soil C density for each forest in the eastern Arc was computed as the product of weight of soil per unit area (kg ha^{-1}), bulk density, and the average percent C for each depth. Biomass and carbon storage by different plant communities was also estimated using similar procedure as those used for the entire forests.

RESULTS

Wood density, tree volume and biomass Models

Table 1a shows the prediction models developed to estimate the biomass of different tree parts and total biomass for the Kilimanjaro forest (model 1-4) the one used to estimate tree volume hence biomass and carbon for the Eastern Arc forests. Table 2(a) show the sample tree species used in the development of the biomass models for Kilimanjaro and 2(b) for those species used to develop volume prediction models for the Eastern Arc forests.

Wood density from the sample trees in the Eastern Arc ranged from 0.24 g cm^{-3} to 0.85 g cm^{-3} with an average of 0.58 g cm^{-3} (Table 2). The average wood density was consistent with wood densities reported in other studies for tropical Africa (Brown and Lugo, 1992; Brown, 1997; Reyes *et al.*, 1992). The regression model developed for the determination of tree volume showed an exponential relationship between tree volume and DBH in the form of $V = 194.8803\text{DBH}^{2.3982}$ ($r^2 = 0.99$, $p < 0.0001$) where $V =$ tree volume (cm^3), DBH = breast height diameters in centimeters (Fig 3).

Table 1: Biomass models for various parts of trees in a montane rain forest ecosystem northern Tanzania

Dependent Variable	Model	r ²	SE	P
(1) Total Biomass	$\ln\text{TOTBIOM} = -1.76 + 2.21\ln\text{DBH}$	0.81	0.215	<0.005
(2) Stem Biomass	$\ln\text{STBIOM} = -2.47 + 2.31\ln\text{DBH}$	0.79	0.236	<0.005
(3) Branch Biomass	$\ln\text{BRBIOM} = -2.14 + 1.86\ln\text{DBH}$	0.63	0.284	<0.005
(4) Leaf Biomass	$\ln\text{LFBIOM} = -3.71 + 1.65\ln\text{DBH}$	0.61	0.260	<0.005
(5) Tree Volume	$V = 194.8803\text{DBH}^{2.3982}$	0.99	0.16	<0.0001

Model 1 – 4 (Kilimanjaro) $\ln x = a + b\ln\text{DBH}$
 Model 5 (Eastern Arc) $x = a\text{DBH}^b$

Where: x = biomass content (kg/tons)
 DBH = Breast Height Diameter
 (1.3m above the ground)
 V = Tree Volume.

Table 2(a): Sample trees used for development of biomass and carbon prediction models for Kilimanjaro montane forests Northern Tanzania

Species	Family
<i>Albizia gummifera</i>	Mimosaceae
<i>Aphloia theaeformis</i>	Flacourtiaceae
<i>Cassipourea malosana</i>	Rhizophoraceae
<i>Ilex mitis</i>	Aquifoliaceae
<i>Macaranga kilimandscharica Pax</i>	Euphorbiaceae
<i>Maesa lanceolata</i>	Myrsinaceae
<i>Markhamia platycalyx</i>	Bignoniaceae
<i>Mussaenda microdonta</i>	Rubiaceae
<i>Nuxia congesta</i>	Loganiaceae
<i>Ocotea usambarensis</i>	Lauraceae
<i>Olinia usambarensis</i>	Oliniaceae
<i>Pauridiantha paucinervis</i>	Rubiaceae
<i>Polycias fulva</i>	Araliaceae
<i>Rapanaea rhododendroides</i>	Myristicaceae
<i>Syzygium guineense</i>	Myrsinaceae
<i>Vangueria sp</i>	Rubiaceae
<i>Vernonia sp</i>	Asteraceae

Forest biomass and carbon storage in trees

The biomass for tree >10cm dbh in the Kilimanjaro forest was 601.8 ± 10 (SD) t ha⁻¹. This aggregates to 295.0 ± 8 (SD) t ha⁻¹ C. The biomass of trees ≥ 6 cm dbh in the eastern Arc forests was 1055 ± 35 (SD) t ha⁻¹ for the Usambaras and 784 ± 20 (SD) t ha⁻¹ for the Ulugurus. This aggregates to 517 ± 17 (SD) t ha⁻¹ and 384 ± 10 (SD) t ha⁻¹ C for the Usambara and Uluguru respectively (Table 3). The low variance (SD) in biomass and carbon estimates among different plots shows the consistency and precision of the method employed in predicting biomass and carbon storage in these forests. The Usambara forest has higher basal area, biomass, and C but lower stem density. The difference in C storage between the three sites can obviously be attributed to differences in disturbance levels and/or forest types and structure. The Usambara forests seem to be relatively intact compared to the Ulugurus and Kilimanjaro, which has higher rates of human use. Further, tree sizes, stocking

and basal area differ between the two forests whereby the forest with higher basal area will likely have higher biomass and carbon storage (Table 3).

Soil organic carbon

At 1498 t ha⁻¹, the soil organic C density was 72% and 80% higher in Kilimanjaro than the Usambaras and Ulugurus respectively (Table 3). The C density at the 15-30 cm depth was 68% of that at the 0-15 cm depth in the Usambaras and 80% in the Ulugurus. Soil C density was 74% and 64% of the amount contained in tree biomass for Usambara and Uluguru respectively. In Kilimanjaro the soil C density was five times the amount contained in tree biomass. The proportion of soil C in the Usambara and Ulugurus would be higher if there is a significant amount of C stored below 30cm. In Kilimanjaro the analysis was done to 100cm depth.

Table 2(b): Sample tree species for biomass and carbon assessment in the Eastern Arc Mountain Forests.

Species Name	Family	Density (g cm ⁻³)	Dbh (cm)	Height (m)
<i>Polycias fulva</i> (Hiern.) Harms.	Araliaceae	0.24	64.0	33.6
<i>Aningeria adolfi-friedercii</i> (Engl.) Robyns & Gilb.	Sapotaceae	0.43	88.5	51.5
<i>Macaranga kilimandscharica</i> Pax.	Euphorbiaceae	0.45	42.2	24.0
<i>Cussonia spicata</i> Thunb.	Araliaceae	0.49	32.5	27.0
<i>Entandrophragma deiningeri</i> Harms.	Meliaceae	0.49	195.0	60.5
<i>Albizia gummifera</i> (Gmel.) CA. Sm.	Mimosaceae	0.52	37.8	29.0
<i>Pachystela msolo</i> Engl.	Sapotaceae	0.54	62.4	39.0
<i>Craibia brevicaudata</i> (Vatke) Dunn	Papilionaceae	0.55	63.2	30.7
<i>Podocarpus usambarensis</i> Pilg.	Podocarpaceae	0.55	30.3	24.0
<i>Sorindeia usambarensis</i> Engl.	Anacardiaceae	0.56	31.0	22.0
<i>Trichoscypha ulugurensis</i> Mildbr.	Anacardiaceae	0.56	56.2	34.2
<i>Ficalhoa laurifolia</i> Hiern.	Theaceae	0.57	66.4	33.8
<i>Allanblackia stuhlmanii</i> Engl.	Clusiaceae	0.58	87.5	46.5
<i>Caloncoba welwitschii</i> (Oliv.) Gilg.	Flacourtiaceae	0.58	17.9	13.5
<i>Syzygium guineense</i> (Willd.) DC	Myrtaceae	0.58	90.5	39.0
<i>Teclea amaniensis</i> Engl.	Rutaceae	0.58	27.9	27.5
<i>Newtonia buchananii</i> (Bak.) Gilb & Bout	Mimosaceae	0.59	55.0	34.0
<i>Symphonia globulifera</i> L.f.	Clusiaceae	0.59	63.1	39.0
<i>Dicranolepis usambarica</i> Engl.	Thymelaeaceae	0.60	68.8	49.5
<i>Cola greenwayii</i> Bren.	Sterculiaceae	0.62	39.0	30.0
<i>Drypetes usambarica</i> (Pax) Hutch.	Euphorbiaceae	0.62	19.0	19.0
<i>Maytenus acuminiatus</i> (L.f) Loes	Celastraceae	0.62	23.6	26.0
<i>Ocotea usambarensis</i> Engl.	Lauraceae	0.63	19.7	37.5
<i>Strombosia scheffleri</i> Engl.	Olacaceae	0.63	24.0	21.0
<i>Dasylepis leptohylla</i> Gilg.	Flacourtiaceae	0.64	13.5	23.5
<i>Cassipourea congoensis</i> DC.	Rhizophoraceae	0.66	45.5	23.2
<i>Parinari excelsa</i> ssp <i>holstii</i> (Engl.) R Grah.	Chrysobalanaceae	0.66	79.0	41.5
<i>Aphloia theaeformis</i> (Willd.) Benth.	Flacourtiaceae	0.69	34.0	21.0
<i>Afrocrania volkensii</i> (Harms) Hutch	Cornaceae	0.81	52.4	34.0
<i>Isobertinia scheffleri</i> (Harms.) Greenway	Caesalpiniaceae	0.85	134.5	54.0
	Average	0.58	55.5	32.9

Table 3: Basal area, stem density, biomass, and carbon stocks of three afro-montane rain forests of Tanzania. (\pm) represents the standard deviation (variances) among plots.

Parameter	USAMBARA	ULUGURU	KILIMANJARO
Basal Area (m ² ha ⁻¹)	104±49	83±53	NA
Stem density (stems ha ⁻¹)	988 ± 376	1161 ± 397	NA
Tree Biomass (t ha ⁻¹)			
Aboveground	872±28	648±16	476.2±8
Roots	183±7	142±4	125.6±2
Total	1064±35	790±20	602±10
Tree Carbon (t ha ⁻¹)			
Aboveground	427±14	318±8	234±5
Roots	90±3	70±2	62±3
Total	517 ± 17	388± 10	295±8
Soil Organic Carbon (t ha ⁻¹)			
0 – 15 cm depth	246 ± 129	164 ± 57	NA
15 – 30 cm depth	172 ± 70	131 ± 48	NA
Total	418 ± 100	295 ± 53	1498

DISCUSSION

We believe that our estimates of carbon storage potential in montane rain forests are among the pioneer studies in East Africa that consider both

the vegetation and soil potential to accumulate carbon. Most studies have considered on the above ground components of a forest ecosystem. The biomass and C density estimates for the Usambaras in this study are identical to earlier

estimates for Mazumbai Forest Reserve (Hall, 1980), e.g., 1162 ton ha⁻¹ biomass (569.4 t ha⁻¹ C). On the other hand the estimates are higher than those of other studies of moist tropical forests (Brown *et al.* 1991; Brown 1997), and 60-year rotation plantation grown *Tectona grandis* (Teak) in Tanzania, e.g., 244 t ha⁻¹ C, (O'Kting'ati *et al.*, 1998). The C storage potential is on the higher side of that reported for tropical moist forests. Brown *et al.* (1991) observed that only about 6% of mature forests in tropical Asia had biomass estimates > 500 t ha⁻¹ (245 t ha⁻¹ C) while more than 61% of the forests had biomasses less than 250 t ha⁻¹ (122.5 t ha⁻¹ C). Yamakura *et al.* (1986) reported an aboveground biomass of 509 t ha⁻¹ in undisturbed Dipterocarpaceae forest in Indonesia. Edwards and Grubb (1977) reported a biomass of 335 t ha⁻¹ in tropical forests of Papua New Guinea. Lundgren (1978) estimated a biomass of 487.3 t ha⁻¹ (238.8 t ha⁻¹) in a West Usambara forest. The high values of the forests in this study can be attributed to the relatively intact conditions of the forests with little or no anthropogenic (human induced) disturbances. Though used by surrounding communities, the catchment forests of Tanzania are well respected by neighboring local communities for their perceived importance, especially in the maintenance of water supply. This reduces their vulnerability to severe human impacts (Temba, 1996). The Kilimanjaro forest would likely have higher biomass and carbon values in trees if it were not for degradation that is occurring. The forest has been under sustained exploitation pressure of large valuable timber species such as *Ocotea usambarensis* and *Podocarpus* spp. Removal of these large trees create gaps that become invaded by pioneer species like *Macaranga capense* and *Polyscias fulva*. Harvesting of poles and other small round wood also may contribute to lower biomass and C. Forests that have been subjected to human disturbance tend to have lower biomass than their potential (Brown *et al.*, 1991; Brown, 1997). Further most estimates of biomass in tropical forests have tended to use a minimum dbh of 10cm. However, overestimates resulting from computational and sampling procedure should not be underestimated. The use of biomass expansion factor from other studies, tree volume determination from diameter using the cone formula, and possible bias in plot locations that may have favored relatively fully stocked sites could have resulted into overestimation of stocking levels, basal area and hence biomass.

Despite all these shortfalls, estimates from the Ulugurus seem to fall more closely within other studies in tropical forests.

The soil organic C density estimates in the Eastern Arc forests are different from those given by Tate *et al.* (1993) cited in Ford-Robertson *et al.* (2000) for Australian forests whereby the soil carbon is estimated to be twice the quantity in vegetation. The difference is probably due to the estimates in the other study being based on soil analysis down to 100 cm depth as opposed to 30 cm in this study. Although soil organic carbon is normally concentrated in the top 30 cm, there can be substantial amounts down to 200 cm resulting from dead roots especially in montane forests where roots may grow deeper than 30cm (Wojick, 1999). Observations in Kilimanjaro however compare well with those of Edwards and Grubb (1977) in a montane rain forest in Papua New Guinea (1200 t h⁻¹) and are much higher than 247 t h⁻¹ reported by Lundgren (1978) for a west Usambara montane forest. Our study included C in the forest floor and fine roots that were not accounted for in the other studies.

Most forests of the Eastern Arc Mountains are old growth protected reserves that are relatively undisturbed. Although questioned by Lugo and Brown (1986) and Borchers (1991), a steady state soil C concentration may be assumed for such old growth forests (Jenny, 1980; Johnson *et al.*, 1991). These forests are also likely to have relatively stable soil organic C pools in the form of humic substances with long residence times. Humic substances, which make about 65-75% of the organic matter in inorganic soils are relatively resistant to biological degradation and have long storage time ranging from decades to centuries (Schnitzer, 1982; Wojick, 1999). Important characteristics exhibited by some humic fractions are resistance to microbial degradation and the formation of stable water-soluble and water insoluble complexes with metal ions and hydrous oxides and interactions with clay minerals. The high % organic matter in these forests (>6% average) provides physical protection by formation of complexes between organics and mineral particles (i.e., aggregation), which may extend the turnover time for labile soil organic matter (Anderson and Paul, 1984; Borchers, 1991). Kobak and Kondrasheva (1991) estimated a 4,500 years residence time for both labile and stable C pools (range 3,000 – 6,000 years). If forests are assumed to be in dynamic

equilibrium with constant additions of organic matter from leaves and dead wood, their potential to continue storing this constant amount of carbon is high when undisturbed. The forests are also at high altitudes where temperatures are relatively low and organic matter decomposition rates can be low. High elevation plant communities have higher soil C and total C than those in low altitudes.

The fate of at least 10% of the carbon dioxide added to the atmosphere by burning fossil fuels is still unaccounted for (Botkin *et al.*, 1993; Cushman *et al.*, 2000; Karl *et al.*, 1997; Lal *et al.*, 1993; O'Kting'ati *et al.*, 1998). One possible sink for this missing carbon have been suggested to be biological uptake by terrestrial ecosystems, especially forests (Botkin and Simpson, 1990; Wisniewski and Sampson, 1993; Dixon *et al.*, 1993; Sampson; 1993; Mendelson and Rosenberg, 1994; Winjum, *et al.*, 1997; Brown, 1996, 1997; Entry and Emmingham, 1998; Wojick, 1999). Ecosystems that can store large amounts of carbon especially, where they cover extensive areas like the forests in this study, are likely to be significant for carbon emission mitigation. Conservation and management of these forests may also mean some permissible harvesting. With lawful harvesting to recover some of their economic values, much of the harvested wood can end up in products with a long life span, increasing carbon storage in durable wood products.

CONCLUSIONS

It is evident that there is a tremendous capacity for the natural forests in Tanzania to store C and their management has high potential to mitigate carbon emissions. If well managed they can be used as a basis for emission offset trading and conservation credits (Brown, 1999). Montane rain forests in Tanzania make up more than 40 percent of the forest area in Tanzania. Despite 25% of the country being preserved in parks, forests are being reduced rapidly in some regions, threatening the very existence of the forests. Among the major options for mitigation of C emissions include avoiding emissions and conserving the existing C pools on the land (slowing down deforestation or improving forest harvesting) (Brown 1999). The conservation of extensive forest cover that is threatened by population pressure like the montane forests of Tanzania, will greatly contribute to emission

avoidance and conservation of the existing carbon pools as mitigation measures. As long as the status of these forests remains unchanged, their role as a carbon store is significant in Tanzania's effort to mitigate global warming.

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