CARBON STORAGE IN AFROMONTANE RAIN FORESTS OF THE EASTERN ARC MOUNTAINS OF TANZANIA: THEIR NET CONTRIBUTION TO ATMOSPHERIC CARBON

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MUNISHI, P. K. T. & SHEAR, T. H. 2004. Carbon storage in afromontane rain forests of the Eastern Arc Mountains of Tanzania: their net contribution to atmospheric carbon. With the increasing concern about rising atmospheric carbon dioxide concentration and its implications for global climate, the role of terrestrial vegetation, and especially tropical forest management have received attention as a means of mitigating carbon (C) emissions. Thus, inventorying carbon pools in these ecosystems has become important for understanding the global C budget. Tree dimensions, wood basic density and analyses of soil C concentration were used to quantify the biomass and C pools of the Eastern Arc Mountains of Tanzania. Tree C density was estimated as product of wood volume, basic density, and proportion of C in wood. Soil C density was estimated as product of soil volume, bulk density and per cent C. Tree biomass was 1055 ± 35 and 790 ± 20 t ha^{-1} for the Usambaras and Ulugurus respectively. These aggregated to 517 ± 17 t ha^{-1} C in the Usambaras and 388 ± 10 t ha^{-1} in the Ulugurus. The soil organic C density was 418 ± 100 t ha^{-1} in the Usambaras and 295 ± 53 t ha^{-1} in the Ulugurus. Mid-altitude plant communities had higher C storage potential compared with high altitude plants. This capacity for C storage, population pressure and the extensiveness of these forests in the region make their conservation a global significance for C emission mitigation.

Key words: Biomass – plant communities – soil organic carbon – mitigation

MUNISHI, P. K. T. & SHEAR, T. H. 2004. Penyimpanan karbon di hutan hujan gunung Afrika di Pergunungan Arka Timur Tanzania: sumbangan bersih terhadap karbon atmosfera. 2004. Peningkatan kepekatan karbon dioksida di atmosfera dan kesannya terhadap iklim dunia semakin membimbangkan. Oleh itu, peranan tanaman daratan dan terutamanya pengurusan hutan tropika telah mendapat perhatian sebagai cara mengurangkan pembebasan karbon (C). Justeru, inventori takungan C dalam ekosistem ini sangat penting untuk memahami bajet C sedunia. Dimensi pokok, ketumpatan asas kayu serta analisis kepekatan C tanih diguna untuk mendapatkan kuantiti biojisim dan takungan C di Pergunungan Arka Timur, Tanzania. Ketumpatan C pokok dianggar berdasarkan hasil isi padu kayu, ketumpatan asas dan juga pecahan C dalam kayu Ketumpatan C tanih pula dianggar berdasarkan hasil isi padu tanih, ketumpatan pukal dan peratus C Biojisim pokok ialah masing-masing 1055 ± 35 t ha^{-1} dan $790 + 20$ t ha^{-1} di hutan Usambara dan Uluguru Nilai ini bersamaan dengan 517 t ha^{-1} C di Usambara dan 388 ± 10 t ha^{-1} C di Uluguru Ketumpatan C organik tanih ialah 418 ± 100 t ha^{-1} di Usambara serta 295 ± 53 t ha^{-1} di Uluguru Komuniti pokok di aras ketinggian pertengahan mempunyai potensi penyimpanan C yang lebih tinggi berbanding pokok di aras tinggi Keupayaan penyimpanan C, tekanan populasi dan keluasan kedua-dua hutan di kawasan ini menjadikan usaha memulihara kedua-dua hutan ini satu kepentingan sejagat demi mengurangkan pembebasan C

Introduction

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 (Wisniewski & Sampson 1993, Brown 1997, Wayburn 2000). With the increasing concern about the rise in atmospheric carbon dioxide (CO_2) concentration and its implications for global climate, the role of tropical forest management in mitigating CO_2 emissions is receiving attention. Thus, determining the amount of changes in vegetation biomass has become important for understanding the global C budget, including the fate of CO_2 produced by burning of fossil fuels and forest clearing (Detwiler & Hall 1988, Brown *et al.* 1993), and the management of existing C pools on land for emission mitigation (Brown 1999).

Biomass and carbon for tropical forests are globally undergoing greatest change. However, reliable estimates for them are few (Brown 1997). Biomass and carbon influence the global C cycle. Tropical forests have the greatest potential for mitigating atmospheric CO_2 emissions through conservation and management (Brown *et al.* 1996, Munishi *et al.* 2000). Changes in the cover, use, and management of forests produce sources and sinks of CO_2 that are 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). About 50% of the forest biomass is C (Chidumuyo 1993, Brown 1997). This amount is the potential percentage of biomass C that can be added to the atmosphere as CO_2 when the forest is cleared for other landuses. Likewise it is also the percentage of biomass CO_2 that can be removed from the atmosphere by restoring forests or establishing plantations (Brown 1997).

Based on the United Nations Framework Convention on Climate Change (UNFCCC) of 1992, mitigation plans for greenhouse gas emissions have to be formulated by different countries to arrest the problem of global warming. Options for mitigation include avoiding emissions, conserving existing C pools on land (slowing down deforestation or improving forest harvesting), expanding C storage in forest ecosystems by increasing the area and/or C density of forests (e.g. by plantations, agroforests, natural regeneration and soil management) (Dixon *et al.*

1994, Dixon 1996, Brown 1999), increasing storage in durable wood products, and substituting sustainably-grown wood for energy intensive and cement-based products (e.g. biofuels, construction materials) (Brown *et al.* 1996, Brown 1999). An analysis of the potential of different ecosystems to sequester or store carbon is a key to understanding whether the corrective measures taken in landuse changes and forest management are likely to create net C sources or sinks. Such assessments are also fundamental in quantifying pathways for ecosystem C fluxes and sequestration.

The national greenhouse gas inventory of sources and sinks in Tanzania (Anonymous 1994) has identified landuse changes and forest management as the most important sources and sinks of anthropogenic CO_2, although there is no quantitative estimates of the magnitude of these sources and sinks. Forest ecosystems in Tanzania occupy more than 45% of the land area (Anonymous 1989) and more than 50% of the moist forests are confined to the Eastern Arc Mountains. These forests have high carbon density and potential for mitigating CO_2 emissions (Munishi *et al.* 2000) but their assessment and quantification are still inadequate.

The major objective of this study was to evaluate the contribution of the Eastern Arc Mountain forests of Tanzania to C emission mitigation. Specifically the study assessed biomass and carbon stock in trees (stems, branches and roots) and soils of two afromontane rain forests using some of the commonly measured variables in forest studies, namely, diameter at breast height (DBH), height, wood density, and soil C concentrations to evaluate the net contribution to atmospheric C through biomass accumulation and soil carbon.

Materials and methods

Study sites

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 2200 km^2. 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, namely, 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 2000 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 & Lovett 1979, Lovett 1996).

The study sites in the west Usambaras were the Mazumbai and Kisimagonja Forest Reserves (4° 50' S, 38° 30' E), situated within an elevation range of 1300 to 1910 m. The monthly rainfall averages > 50 mm with mean annual rainfall of 1300 mm (Hall 1980, Munishi 2001). The vegetation consists of lower montane to montane evergreen rain forests (Figure 1).

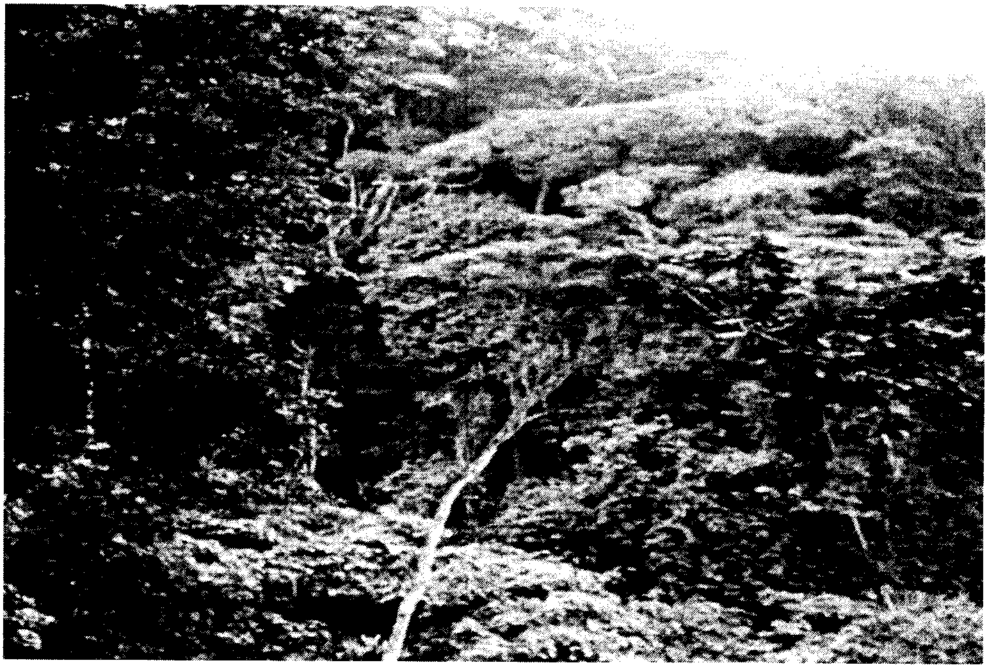

Figure 1 A photograph showing part of the forests studied at the Usambaras, Eastern Arc Mountains of Tanzania

The Uluguru Mountains (7° 02'–7° 16' S and 38° 0'–38° 12' E) 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 2900–4000 mm on the eastern windward slopes and 1200–3100 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 & Pócs 1993). In the Ulugurus, the study site was the Uluguru North Forest Reserve with lower montane, submontane, and montane evergreen rain forests (Figure 2).

Figure 2 A photograph showing part of the forests studied at the Ulugurus, Eastern Arc Mountains of Tanzania

Data collection

One hundred 0.02 ha rectangular plots (20 × 10 m) 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. Plots were established on line transects oriented along elevation gradients. Ten transects were established in each forest with an average length of 1000 m starting from the forest edge towards the ridge top to the highest point. Distance between transect lines were approximately 200 m. 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 to 80 m. For every plot that fell on a completely treeless site, a randomly selected nearby adjacent area with trees was established for measurement purposes. All trees in each plot with DBH ≥ 6 cm were identified and measured for DBH. A total of 120 (60 from each forest) sample trees of 30 different species (two from each species) were selected from every second plot site and measured for DBH using callipers or diameter tape, and total height using a Suunto hypsometer. The sample trees were selected to represent the most common tree species in these forests but need not be within the plot, but

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 ± 2 °C to constant weight and used to compute basic density. Soil samples were collected from each plot at three points along the center line (5 m, 10 m and 15 m) and at two different depths (0–15 cm and 15–30 cm). The three samples from each depth were combined, air dried, and passed through a 0.2-mm sieve. Another set of 40 soil cores, i.e. 20 from each 0–15 cm and 15–30 cm depths, were collected from selected areas of each forest at every fifth plot using bulk density core samplers. The soil cores were then oven dried to constant weight for the determination of bulk density. Wood core volumes were computed as the product of their cross-sectional areas and lengths. The 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. Per cent soil C was determined using a CHN elemental analyser (model NC2100, CE Instruments).

Data analyses

Tree volumes were computed as the product of 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 DBH and density of each of the two trees representing a species were also calculated. 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 tree volume and wood basic density (Malimbwi *et al.* 2000). Different wood basic densities were used to compute tree biomass. These included the specific species density for species with known densities in different plots not represented in the sample trees, family averages for species that were different from the sample trees whose densities were not known but belong to a family whose density was known, or sample tree averages values for species belonging to the sample trees. Individual tree biomass was aggregated to plot biomass and divided by plot area to obtain biomass density (metric t ha^{-1}). An average biomass expansion factor (BEF) (Brown 1997) of 29% was used to estimate the biomass of branches and foliage based on estimates by Hall (1980) and Munishi *et al.* (2000). Root biomass of 22% was based on estimates by Brown and Lugo (1992) 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.

The per cent 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 (Chidumuyo 1993, Malimbwi *et al.* 1994, Brown 1997, Ford-Robertson *et al.* 2000, Munishi *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 per cent C for each depth. The plant composition data were analysed for plant communities and species associations using agglomerative cluster analysis and indicator species analysis (Dufrene & Legendra 1997). Biomass and carbon storage by different plant communities was also estimated using similar procedure as that used for the entire forest.

Results

Wood density and tree volume

Wood density from the sample trees ranged from 0.24 to 0.85 g cm^{-3} with an average of 0.58 g cm^{-3} (Table 1). The average wood density is consistent with wood densities reported in other studies for tropical Africa (Brown & Lugo 1992, Reyes *et al.* 1992, Brown 1997). The regression model developed for the determination of tree volume showed an exponential relationship between tree volume and DBH in the form of $V = 194.8803 DBH^{2.3982}$ ($r^2 = 0.99$, $p < 0.0001$) where V = tree volume (cm^3) and DBH = breast height diameter (cm) (Figure 3).

Table 1 Sample tree species for biomass and carbon assessment in the Eastern Arc Mountain Forests of Tanzania

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

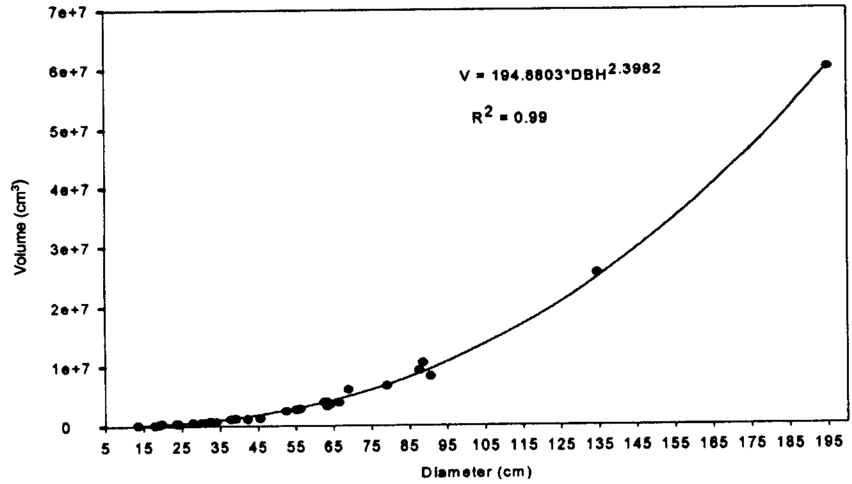

Figure 3 Prediction model for tree volume in two afromontane rain forests of the Eastern Arc Mountains of Tanzania

Forest biomass and carbon storage in trees

The biomass of trees ≥ 6 cm DBH was 1055 ± 35 t ha^{-1} for the Usambaras and 790 ± 20 t ha^{-1} for the Ulugurus (Table 2). This aggregated to 517 ± 17 t ha^{-1} and 388 ± 10 t ha^{-1} C for Usambara and Uluguru respectively (Table 2). The low variances in biomass and carbon estimates between plots showed the consistency and precision of the method employed in predicting biomass and carbon storage in these forests. The Usambara forest had higher basal area, biomass, and C but lower stem density.

Table 2 Basal area, stem density, biomass and carbon stocks of two afromontane rain forests of the Eastern Arc Mountains of Tanzania

Parameter	Usambara*	Uluguru*
Basal area (m^2 ha^{-1})	52 ± 24	42 ± 26
Stem density (stems ha^{-1})	988 ± 376	1161 ± 397
Tree biomass (t ha^{-1})		
Aboveground	872 ± 28	648 ± 16
Roots	183 ± 7	142 ± 4
Total	1055 ± 35	790 ± 20
Tree carbon (t ha^{-1})		
Aboveground	427 ± 14	318 ± 8
Roots	90 ± 3	70 ± 2
Total	517 ± 17	388 ± 10
Soil organic carbon (t ha^{-1})		
0–15 cm depth	246 ± 129	164 ± 57
15–30 cm depth	172 ± 70	131 ± 48
Total	418 ± 100	295 ± 53

* ± SD among plots

Ocotea usambarensis accounted for the highest percentage of biomass and C in both forests (Table 3). Of the 69 tree species in Usambaras, 11 species together contributed about 80% of the total biomass and C. From the other 57 species which accounted for the remaining 20% of biomass and C, 51 species each contributed less than 1% (results not shown). In the Ulugurus, 12 of the 90 tree species each contributed more than 2% of biomass and C, accounting for 76% of the total. Among the remainder 78 species, 68 species each contributed less than 1%. Compared with other species, *Ocotea* was relatively a large tree in these old growth forests. Maliondo *et al.* (2000) observed that *O. usambarensis* dominated the West Usambara natural forest. Only three species with high biomass and C ranking are common to both forests, namely, *O. usambarensis*, *Syzygium guineense* and *Parinari excelsa*.

Soil organic carbon

At 418 t ha^{-1}, the soil organic C density in the Usambaras was 42% higher than in the Ulugurus (Table 2). The C density was highest (246 t ha^{-1}) in Usambara at the 0–15 cm depth, being 43% higher than that at the 15–30 cm depth in the same forest. Soil C density was 80 and 76% of the amount contained in tree biomass for Usambara and Uluguru respectively.

Table 3 Biomass and carbon contribution by different species in two afromontane rain forests of the Eastern Arc Mountains, Tanzania

Local name	Scientific name	Usambara Biomass t ha^{-1}	Usambara C t ha^{-1}	Usambara %	Uluguru Biomass t ha^{-1}	Uluguru C t ha^{-1}	Uluguru %
Mkulo	*Ocotea usambarensis*	226.9	111.0	29.4	151.9	74.4	24.9
Mshihwi	*Syzygium guineense*	93.2	45.6	12.4	35.1	17.2	5.7
Mnyasa	*Newtonia buchananii*	59.7	29.2	7.7			
Muula	*Parinari excelsa*	58.5	28.7	7.6	37.9	18.6	6.2
Mpigamagasa	*Isoberlinia scheffleri*	34.3	16.8	4.4			
Msizizi	*Dicranolepis usambarica*	37.9	18.6	4.9			
Mmandai	*Agauria salicifolia*	29.3	14.4	3.8			
Kihambile	*Drypetes usambarica*	22.1	10.9	2.9			
Msambu	*Allanblackia stuhlmannii*	20.6	10.1	2.7			
Msambia	*Pachystela msolo*	17.6	8.7	2.3			
Kuti	*Aningeria adolfi-friedericii*	16.9	8.3	2.2			
Msese	*Ficalhoa laurifolia*				92.5	45.3	15.1
Mngobwe	*Symphonia globulifera*				25.8	12.7	4.2
Mkenge	*Albizia gummifera*				21.6	10.6	3.5
Mkani	*Allanblackia uluguruensis*				20.1	9.9	3.3
Msangana	*Strombosia scheffleri*				19.7	9.7	3.2
Mgida	*Macaranga kilimandscharica*				18.2	8.9	2.9
Mpekawake	*Afrocrania volkensii*				13.7	6.7	2.2
Msambwa	*Chrysophyllum gorungosanum*				13.6	6.7	2.2
Mnyagengu	*Trychoscypha uluguruensis*				13.1	6.4	2.1

Note: Only species which contributed more than 2% biomass and carbon are shown.

Carbon distribution and storage in different plant communities

The C storage potential differed between plant communities (Table 4). High elevation communities were generally associated with low C storage in trees but high soil organic C. Mid-elevation communities had the highest tree C but lower soil organic C compared with high elevation communities. In the Usambaras, the *O. usambarensis-S. guineense-P. excelsa* community had the highest tree C and total C density but identical soil C density to *Agauria salicifolia-O. usambarensis-C. liebertina* community (Table 4). Although *A. salicifolia-O. usambarensis-C. liebertina* community ranks fourth in tree C, its soil C was the highest and was the second in total C due to its high soil organic C.

In the Ulugurus, *O. usambarensis-Allanblackia uluguruensis-Symphonia globulifera* community had the highest soil and total C, but lower tree C than *Trichocypha uluguruensis-Strombosia scheffleri-Dasylepis integra* community.

Table 4 Carbon storage by different plant communities in two afromontane rain forests of the Eastern Arc Mountain forests, Tanzania

Forest	Community*	Tree C ($\mathrm{t\ ha^{-1}}$)	Soil Organic C ($\mathrm{t\ ha^{-1}}$) 0–15 cm	15–30 cm	Total C ($\mathrm{t\ ha^{-1}}$)	% C	Mean Elevation (m)
Usambara	*Sorindeia*	355 ± 187	147 ± 73	110 ± 59	612	6.8 ± 4	1468
	Strombosia	449 ± 221	168 ± 59	146 ± 59	763	8.2 ± 3	1515
	Syzygium	320 ± 155	219 ± 160	141 ± 57	680	9.5 ± 5	1527
	Ocotea	564 ± 302	338 ± 101	216 ± 47	1118	14.6 ± 4	1662
	Agauria	333 ± 190	338 ± 93	224 ± 42	895	14.9 ± 3	1770
Uluguru	*Myrianthus*	288 ± 173	128 ± 25	92 ± 29	508	5.8 ± 2	1682
	Trichocypha	467 ± 411	139 ± 41	127 ± 46	733	6.9 ± 2	1750
	Symphonia	182 ± 74	164 ± 41	127 ± 24	473	7.6 ± 2	1901
	Ocotea	426 ± 374	206 ± 82	156 ± 61	788	9.4 ± 4	1903
	Syzygium	163 ± 89	166 ± 46	131 ± 39	454	7.7 ± 2	1998

* Communities in order:

Usambara:

- *Sorindeia usambarensis-Parinari exelsa-Newtonia buchanani* forest
- *Strombosia scheffleri-Craibia brevicaudata-Pachystela msolo-Isoberlinia scheffleri* forest
- *Syzygium guineense-Sorindeia usambarensis-Parinari excelsa-Newtonia buchanani* forest
- *Ocotea usambarensis-Syzygium guineense-Parinari excelsa* forest
- *Agauria salicifolia-Ocotea usambarensis-Cryptocarya liebertina* forest

Uluguru

- *Myrianthus arborea-Cussonia spicata-Albizia gumifera-Afrocrania volkensii* forest
- *Trichocypha uluguruensis-Strombosia shefflleri-Dasylepis integra* forest
- *Symphonia globulifera-Cassipourea malosana-Syzygium guineense* forest
- *Ocotea usambarensis-Allanblackia uluguruensis-Symphonia globulifera* forest
- *Syzygium guineense-Allanblackia uluguruensis-Garcinia volkensii* forest

± SD

Five different plant communities (forest types) were each identified in a different but parallel study in both the Usambara and Uluguru forests (Munishi 2001)

Trichocypha ulugurensis-S. scheffleri-D. integra community had the highest tree C but ranked second in total C (Table 4). On the other hand, *O. usambarensis-Allanblackia ulugurensis-Symphonia globulifera* community ranked the highest in total C due to higher soil C. Communities (forest types) with high soil C are at high altitudes where decomposition rate is low with possible accumulation of organic matter.

Discussion

The biomass and C density estimates in this study are similar to earlier estimates for Mazumbai Forest Reserve (1162 t ha^{-1} biomass, 569.4 t ha^{-1} C) (Hall 1980), but higher than those of other studies for moist tropical forests (Brown *et al.* 1991, Brown 1997), and a 60-year rotation plantation grown *Tectona grandis* in Tanzania (244 t ha^{-1} C) (O'Kting'ati *et al.* 1998). The C storage potential is higher than that reported for tropical moist forests. Brown *et al.* (1991) concluded 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 biomass 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. The high values of aboveground biomass in the forests of this study can be attributed to the relatively intact conditions of the forests with little or no anthropogenic disturbances. Although used by surrounding communities, the catchment forests of Tanzania are well respected by neighbouring local communities for their perceived importance, especially in the maintenance of water supply. This reduces their vulnerability to severe human impacts (Temba 1996). Forests that have been subjected to human disturbances tend to have lower biomass than their potential (Brown *et al.* 1991, Brown 1997). Further, most estimates of biomass in tropical forests were accumulated based on a minimum DBH of 10 cm. This study used a lower diameter limit of 6 cm, which might have contributed to the observed high values of biomass by inclusion of more trees per unit area. On the other hand, overestimates resulting from computational and sampling procedures may not be undermined. 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 favoured relatively fully stocked sites could have resulted in overestimation of stocking levels, basal area and, hence, biomass. Despite all these, estimates from the Ulugurus seem to fall more closely within other studies in tropical forests.

The difference in C storage between the two sites can obviously be attributed to differences in disturbance levels and/or forest types and structure. The Usambara forests were more intact compared with the Ulugurus, which had higher rates of human use. Further, tree sizes, stocking and basal area differed between the two forests. Usambara forests, with higher basal area, had higher biomass and carbon storage (Table 2).

The soil organic C density estimates in this study are very much lower than values reported for Australian forests (Ford-Robertson *et al.* 2000), where the amount of C per unit area in the soil was estimated to be twice the amount in aboveground vegetation. Also, Munishi *et al.* (2000) found higher C pools in the soil than in the aboveground vegetation for a tropical rain forest in northern Tanzania. The difference is probably due to the depth of soil analysis; the other studies were based on soil analysis down to 100 cm depth as opposed to 30 cm in this study. Although soil organic C 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 30 cm (Wojick 1999).

Most forests of the Eastern Arc Mountains are old growth protected reserves that are relatively undisturbed and have a steady state soil C concentration (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 all humic fractions are resistant 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 percentage of 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 (Borchers 1991). Kobak and Kondrasheva (1991) estimated an average residence time of 4500 years for both labile and stable C pools. 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 and organic matter decomposition rates are low. High elevation plant communities in this study had higher soil C and total C than those at low altitudes.

The differences in tree carbon between plant communities (forest types) may be associated with sizes of tree species that constituted these communities. Forest types with larger trees accumulated more biomass, hence, higher C. Differences in soil organic C between communities may be associated with the quality of litter produced by the species that constituted these communities, as well as elevation ranges in which these communities occurred. Different species produce different types of litter, which decomposes and mineralises at different rates. The higher the quality of litter produced by a given species, the higher the decomposition rate and the lower the accumulation of organic matter. In high elevation communities, organic matter decomposition rate is low due to relatively low temperatures, resulting in accumulation of organic matter.

The fate of at least 10% of the CO_2 added to the atmosphere by burning fossil fuels is still unaccounted for (Botkin *et al.* 1993, Karl *et al.* 1997, O'Kting'ati *et al.* 1998, Cushman *et al.* 2000). One possible sink for this missing carbon have been suggested to be biological uptake by terrestrial ecosystems, especially forests (Botkin & Simpson 1990, Dixon *et al.* 1993, Sampson 1993, Wisniewski & Sampson

1993, Mendelson & Rosenberg 1994, Brown 1997, Winjum *et al.* 1997, Wojick 1999). Ecosystems, like the Eastern Arc forests, can store large amounts of C and are likely to be significant for C emission mitigation. Conservation and management of the Eastern Arc 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

There is apparently a tremendous capacity for the Eastern Arc Mountain forests to store C. The management of these forests has high potential to mitigate C emissions and can be used as a basis for emission offset trading and conservation credits. Such credits have been effective at raising funds for conservation in other countries (Daniel 1995, Casey 1997, Ronald 1997, Brown 1999). Our estimates are first approximations and a preliminary contribution to the assessment of such potential in the Eastern Arc Mountain forests. Further studies to improve these estimates are important. Apart from other values, C storage potential of these forests puts their conservation in global context, especially as the global community turns to terrestrial vegetation management as a means of mitigating CO_2 emissions. Over 37% of Tanzania is covered by extensive forests; most of which are savanna woodlands and montane forests, although there are scattered patches of lowland forests. Montane rain forests like the Eastern Arc forests make up more than 40% of these forests; the Eastern Arc Mountain forests stretch from southern Kenya to southern Tanzania. These forests have high biodiversity and endemism. All these forests are located in high population areas with high rainfall and are therefore increasingly threatened by fuelwood collection by the rapidly expanding population, commercial felling of timber, and expanding agriculture which makes up 58% of the GNP. 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, i.e. by slowing down deforestation or improving forest harvesting (Brown 1999). The conservation of extensive forest cover that is threatened by population pressure like the Eastern Arc forests will greatly contribute to emission avoidance and conservation of the existing C pools as mitigation measures. As long as the status of these forests remains unchanged, their role as carbon store is significant in Tanzania's effort to mitigate global warming. The conservation of these forests, however, needs be planned within the context of both political and socio-economic challenges. Putting value on non-marketable products from these forests, for example carbon emission mitigation, and ensuring that these values can be translated into tangible benefits to the surrounding local communities is a potential challenge.

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