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Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains

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Abstract

We determine the aboveground biomass and carbon storage (ABGC) of trees and the herbaceous layer in miombo woodland in the Eastern Arc Mountains (EAM) of Tanzania. In four 1-ha sample plots in Nyanganje and Kitonga Forests, we measured all trees ≥10 cm diameter alongside height and wood mass density. The plots contained an average of 20 tree species ha^{-1} (range 11–29) and 344 stems ha^{-1} (range 281–382) with Shannon diversity values of 1.05 and 1.25, respectively. We weighted nine previously published woody savannah allometric models based on whether: (i) the model was derived from the same geographical region; (ii) the model included tree height/wood mass density in addition to stem diameter; and (iii) sample size was used to fit the model. The weighted mean ABGC storage from the nine models range from 13.5 ± 2 to 29.8 ± 5 Mg ha^{-1}. Measured ABGC storage in the herbaceous layer, using the wet combustion method, adds 0.55 ± 0.02 Mg C ha^{-1}. Estimates suggest that EAM miombo woodlands store a range of 13–30 Mg ha^{-1} of carbon. Although the estimates suggest that miombo woodlands store significant quantities of carbon, caution is required as this is the first estimate based on *in situ* data.

Key words: carbon storage, composition, Eastern Arc Mountains, miombo woodland, structure

Résumé

Nous déterminons le stock de biomasse de carbone aérien (C_{abg}) dans les arbres et dans la couche herbacée de la forêt à Miombo dans les montagnes de l'Arc Oriental (EAM), en Tanzanie. Dans quatre parcelles d'un hectare délimitées dans les forêts de Nyanganje et de Kitonga, nous avons mesuré tous les arbres ≥10 cm de diamètre en notant leur hauteur et la densité de la masse ligneuse. Les parcelles contenaient en moyenne 20 espèces d'arbres par hectare (*n* compris entre 11 et 29) et 344 troncs par hectare (entre 281 et 382), avec des indices de Shannon respectivement de 1,05 et 1,25. Nous avons pondéré neuf modèles allométriques de savane ligneuse publiés antérieurement en nous basant sur les alternatives suivantes : (i) le modèle est, ou pas, dérivé de la même région géographique; (ii) le modèle inclut la hauteur des arbres/la densité de la masse ligneuse en plus du diamètre du tronc; et (iii) la taille de l'échantillon utilisé correspond au modèle. Le stock de biomasse de carbone aérien (C_{abg}) moyen pondéré issu des neuf modèles va de 13.5 ± 2 à 29.8 ± 5 Mg ha^{-1}. Le stock de biomasse de carbone aérien (C_{abg}) dans la couche herbacée, en utilisant la méthode de combustion humide y ajoute 0.55 ± 0.02 Mg C ha^{-1}. Les estimations laissent penser que les forêts de Miombo des EAM stockent de 13 à 30 MG de carbone par hectare. Bien que les estimations suggèrent que les forêts de Miombo stockent des quantités significatives de carbone, la prudence est de mise parce que ceci est la première estimation fondée sur des données *in situ.*

Introduction

Tropical savannahs with varying degrees of woody vegetation cover 20% of the worlds land surface, with 65% of this biome being in Africa (Thomas & Packham, 2007).

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Woody savannahs dominated by the tree *Brachystegia*, known as miombo woodlands, are one of the most extensive vegetation types in Africa, covering about 2.7 million km^2 of Tanzania, Congo, Angola, Zimbabwe, Zambia, Malawi and Mozambique (Campbell, Frost & Byron, 1996; Thomas & Packham, 2007). In Tanzania, woodland and forest cover are about 340,000 km^2 (MNRT, 1998), with two-thirds of it estimated to be miombo woodland (Fyhrquist, 2002). In the Eastern Arc Mountains, miombo woodland occupies 23% (approximately 1228 km^2) of the forested habitat (HTS, 1997; FBD, 2006). Moreover, the miombo woodland ecosystem represents an important supply of fuel wood, fruits, poles and timber in villages, periurban and urban areas (Desanker *et al.*, 1997; Sileshi *et al.*, 2007).

Miombo is characterized by *Brachystegia* and an understory of grasses, often growing on nutrient-poor soils derived from acid crystalline bedrock. In addition to *Brachystegia*, other important tree genera are *Julbernardia* and *Isoberlinia* (Campbell, Frost & Byron, 1996). The grasses growing in miombo are C4 grasses that grow alongside sedges and shrubs (Frost, 1996). This vegetation type grows in areas where the climate is characterized by mean annual temperatures and precipitation of 18.0–23.1°C and 710–1365 mm (Frost, 1996). Some woodlands are maintained by dry season burning of the grasses, without which they would revert to tropical forest systems, whereas others receive little rainfall to support anything other than woody savannah (Desanker *et al.*, 1997; Sankaran *et al.*, 2005). Miombo savannahs are also home to important animal populations including elephants, lions, buffalos and antelopes and have high bird diversity (Campbell, Frost & Byron, 1996; Frost, 1996).

Total standing aboveground biomass of woody vegetation is often one of the largest carbon pools. This pool comprises of all woody stems, branches and leaves of living trees, creepers, climbers, epiphytes and herbaceous undergrowth (Kurniatun *et al.*, 2001). Previous studies show that aboveground biomass carbon (AGBC) storage in tropical woodlands ranges from 1 to 12 Mg C ha^{-1} year^{-1} (Grace *et al.*, 2006), although others have found higher values of 19.0 ± 8.0 Mg C ha^{-1} (Williams *et al.*, 2008; Munishi *et al.*, 2010). In the Eastern Arc Mountains (EAM) [a global biodiversity hotspot (Burgess *et al.*, 2007)], there is limited quantitative information on carbon stocks in miombo woodlands, despite this ecosystem type covering 23% of the EAM area [Hunting Technical Services (HTS), 1997].

In this study, we quantify miombo woodland structure, species composition, diversity and AGBC of trees and the herbaceous layer using standardized permanent sampling plots. Such quantification may allow income generation through carbon offset trading by local communities. Thereafter, we compare estimates of AGBC in trees using nine published allometric models. Finally, we provide a comparison with other estimates from the literature of carbon storage in miombo woodland in other areas outside EAMs.

Material and methods

Study site

The study site is located in the Udzungwa mountain block of the EAM. We selected two miombo forest sites: Nyanganje Forest Reserve (18,988 ha) of which 17,243 was miombo and Kitonga proposed Forest Reserve (9670 ha) of which 9000 was miombo [Hunting Technical Services (HTS), 1997].

Nyanganje Forest Reserve (Fig. 1) is located at 7°56′ to 8°4′S and 36°39′ to 36°50′E. It covers the south-eastern foothills of the Udzungwa Mountains. There are seven villages on the eastern and southern boundaries, with Udzungwa National Park on the north and west (Malimbwi, Luoga & Hassan, 2002). On the southern slopes, Nyanganje is covered by miombo woodland from 270 to 1000 m and closed-canopy tropical forest above 1000 m. Soils are characterized by red and brown ferralitic latosols developed on Precambrian base rocks (Lovett & Pocs, 1993). The reserve receives oceanic rainfall of 1400 mm year^{-1} and experiences one dry season from June to October with minimum and maximum temperatures of 19°C in July and 27°C in December, respectively (Lovett & Pocs, 1993; Malimbwi, Luoga & Hassan, 2002).

Kitonga proposed Forest Reserve is located in the north of the Udzungwa Mountains at 36° 05′–36° 15′E and 7°35′–7°45′ S at an altitude of 660–1880 m. There are five villages on the southern boundary, Udzungwa National Park on the north-east with Image Forest Reserve to the north. The landscape comprises undulating rocky/stony hills and moderately gentle with clay, loams and sandy soils. Here, miombo woodland occurs at altitudes of 660–1700 m, with sub-montane and montane closed-canopy tropical forest above 1700 m altitude. The rainfall pattern is bimodal, starting from November to March and late May to October. Mean rainfall is 720 mm year^{-1}, and

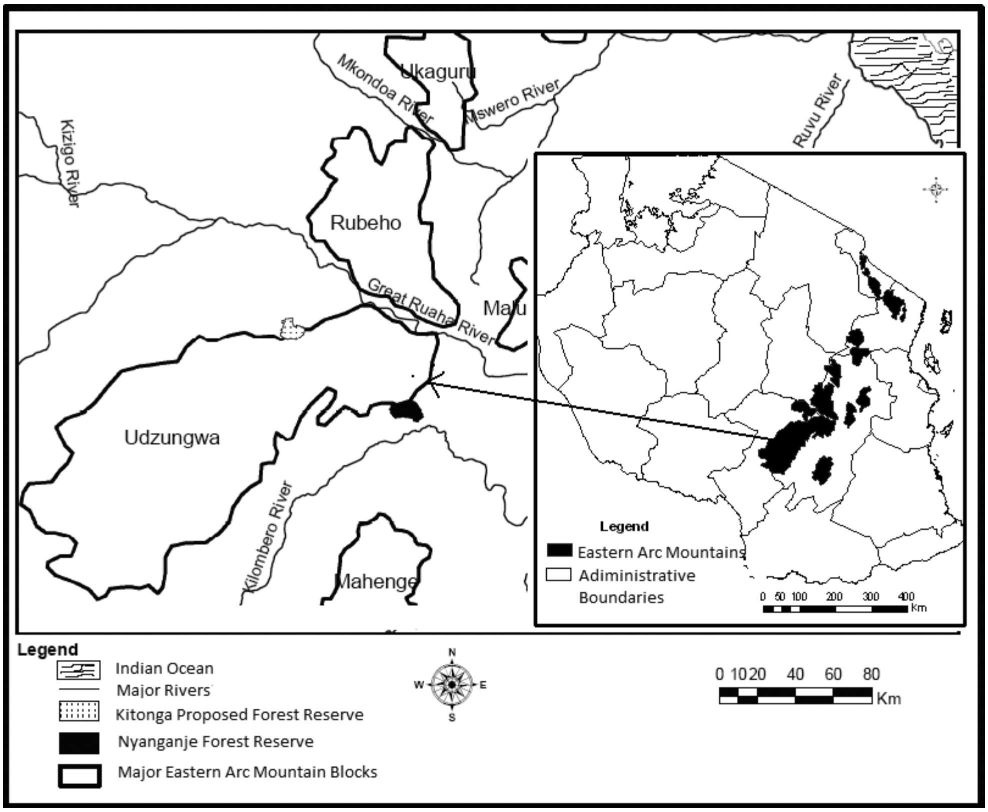

Fig 1 Map of Kitonga proposed forest reserve and Nyanganje forest reserve in the Udzungwa mountain block within the Eastern Arc Mountains, Tanzania

mean temperature ranges from 13.5 to 24.7°C, with maximum temperatures in May and October (Isango, 2007).

Data collection

We collected the biophysical data to quantify the amount of carbon in both trees and the herbaceous layer using standardized inventory techniques. We used topographic maps to identify the miombo woodland habitat, with plot location stratified into four approximately equal-sized elevation bands (270–645 m and 645–1020 m in Nyanganje; 1020–1395 m and 1395–1770 m. in Kitonga). Within each elevation band, we established a 1-ha plot using randomly generated grid co-ordinates, resulting in plots with elevations of 502, 791, 333 and 1500 m. Where the randomly located plots did not contain Miombo or had signs of intense human disturbance, the plots were re-assigned to a new random location within the nearest miombo woodland habitat.

We assessed the plots using the Tropical Ecology, Assessment and Monitoring (TEAM) protocol (Kuebler, 2003). We measured diameter at breast height (DBH) defined as 1.3 m aboveground level, with adjustments for swollen tree bases, injuries, fluting and other deformities. We measured all trees with DBH ≥10 cm and in addition, the heights of three trees (largest, mid and lowest DBH) were also measured. Trees were identified in the field by a local botanist, where those proved difficult voucher specimens were taken for identification at the Tanzania National Herbarium.

Within eight of the 20 × 20 m subplots of the 1-ha plot, we established five 1 × 1 m quadrats, where herbaceous materials were cut at the stem base, collected and fresh mass determined. A portion (50%) of the fresh material was oven-dried to constant weight at 70°C to determine the dry mass (Andason & Ingram, 1993) and grounded to fine powder for total organic carbon determination. We determined the total organic carbon using the wet combustion procedure as described in Nelson & Sommers (1982).

Table 1 Allometric models from different authors as used in this study and their scores for three criteria used to identify the most relevant model for estimating the carbon content of miombo woodlands in the Eastern Arc Mountains

	Equation	Source country	Notes	Locally developed	Large sample size	No. of parameters	Total scores
Brown *et al.* (1989)	$B = \mathrm{EXP}(-1.996 + 2.32 \times \mathrm{LN}(D))$	Dry tropics	Not miombo, specifically developed in dry tropics	0	0	0	0
Chidumayo (1990)	$\mathrm{BL} = 0.51 \times D - 2.11 \mathrm{BTW} = 0.94 \times D - 3.34 \mathrm{BCW} = 22.4 \times D - 215.00$	Zambia	For trees > 1 m height	1	1	0	2
Malimbwi, Solberg & Luoga (1994)	$B = 0.06 \times D^{2.012} \times \mathrm{Ht}^{0.71}$	Tanzania	For trees >5 cm DBH	2	0	1	3
Malimbwi, Solberg & Luoga (1994)	$V = 0.0001 \times D^{2.032} \times \mathrm{Ht}^{0.66}$	Tanzania	For trees >5 cm DBH	2	0	2	4
Frost (1996)	$V = 6.18 \times A^{0.86}$	Zaire, Malawi, Zambia and Zimbabwe	Equation applied on stand basis	1	1	0	2
Abbot, Lowore & Werren (1997)	$V = 10^{(-4.22 + (2.76 \times \mathrm{Log}\ D))}$	Malawi	For canopy trees assumed to be >4 m height or ≥5 cm DBH	1	2	1	4
Chidumayo (1997)	$B = 20.02 \times \mathrm{DBH} - 203.37$	Zambia	For tree ≥10 cm DBH	1	1	0	2
Chamshama, Mugasha & Zahabu (2004)	$B = 0.0625 \times D^{2.553}$	Tanzania	For trees ≥5 cm DBH	2	0	0	2
Chave *et al.* (2005)	$B = 0.112 \times (\mathrm{WD} \times D^2 \times \mathrm{Ht})^{0.916}$	Dry tropics	Not miombo, specifically developed in dry tropics	0	1	2	3

B, biomass (t); *V*, volume (m^3); *A*, basal area ($m^2\ ha^{-1}$); *D*, diameter (cm) at 1.3 m (DBH, breast height); BL, leaf biomass (t); BTW, biomass twig wood (t); BCW, biomass cord wood (t); WD, wood density.

We used an increment borer to extract wood cores (Munishi & Shear, 2004) from at least two trees from each tree species in the four plots. The green (fresh) mass, length and diameter of each core (each end and the middle) were measured in the field and fresh volume calculated. Following this, the samples were dried to constant weight and used to determine dry mass, for calculation of the wood basic density of each species encountered in the plots (defined as fresh volume/dry mass). In total, we determined the wood basic density for 46 different tree species.

Data analysis

To determine tree biomass and carbon, existing allometric models developed in tropical woodland ecosystems were collated following an extensive literature search. We used seven local (East African miombo) and two nonlocal (general tropical woodlands) models (Table 1). Three models utilize tree height measurements, while only three predict tree volume (Malimbwi, Solberg & Luoga, 1994; Frost, 1996; Abbot, Lowore & Werren, 1997; Chave *et al.*, 2005). We then used wood basic density estimates from this study to compute tree biomass from tree volume. We estimate carbon to be 50% of tree biomass (Gibbs *et al.*, 2007; Thomas & Malczewski, 2007; Lewis *et al.*, 2009).

We ranked each model based on three simple criteria, giving each a score of 0, 1 or 2. The first criteria was whether the model was developed locally, with 0 if not developed from sampling miombo woodlands, 1 for miombo woodlands outside the EAM and 2 for those developed using miombo from within the EAM. The second criteria was the number of parameters included in the equation, 0 for DBH or BA (cross-sectional area of a stem) only, 1 for DBH or BA and wood density (WD) or height (H), 2 for models including DBH, H and WD. The final criterion was the sample size used to develop the model, 0 for ≤100 trees, 1 for >100 trees but <1000 trees and 2 for ≥1000 trees. These scores were then used to suggest the best model for estimating carbon density in miombo woodlands in the region and used to weight the models to provide a weighted average of the nine models to utilize the greatest amount of available information to estimate carbon stocks in miombo woodlands in the EAM.

The wet combustion method was used to estimate percentage organic carbon from the dry mass of the herbaceous vegetation (Nelson & Sommers, 1982). The amount of carbon in each sample was calculated as the product of percentage organic carbon and dry mass (Andason & Ingram, 1993). We computed species richness as the total number of species per hectare and species diversity using the Simpson and Shannon diversity indices, calculated using standard equations (Magurran, 1988).

Results

Composition, structure, dominance and diversity

The mean stand density was 344 stems ha^{-1}, ranging from 281 stems ha^{-1} in Kitonga to 382 stems ha^{-1} in Nyanganje (Table 2). In all forests, more stems were observed in the lower DBH class (10–20 cm) and in the lower elevations (502 and 791 m). The mean diameter and basal area ± confidence interval (CI), across all four plots, were 18.1 ± 7.9 cm and 11 ± 0.01 m^2 ha^{-1}, respectively (Table 3). Generally, the size distribution of tree stems showed a normal reversed J shape in the two forests (Table 3).

A total of 45 different tree species from 26 different families were observed in both reserves, with an average species richness of 20 species ha^{-1} (range 11–29). The higher elevation plots in Kitonga had the highest number of tree species (40 tree species), compared with the lower elevation of Nyanganje (35 tree species). There were more

Table 2 Stand density, species richness, diversity indices and carbon storage at Nyanganje and Kitonga forest reserves, Eastern Arc Mountains, Tanzania

Plot no.	Forest type	Elevation (m)	Stand density (stems ha^{-1})	Species richness per plot (No. of Species)	Simpson index	Shannon index	Herb dry mass (Mg ha^{-1})	Herb carbon density (Mg ha^{-1})	Trees carbon stock (Mg C ha^{-1})
1	Nyanganje	502	382	20	0.3	1.9	1.43 ± 0.13	0.56 ± 0.05	27.9 ± 2.3
2	Nyanganje	791	376	18	0.2	2.2	1.54 ± 1.10	0.59 ± 0.04	30.7 ± 2.2
3	Kitonga	1333	335	29	0.2	2.2	0.98 ± 0.03	0.38 ± 0.02	24.1 ± 1.5
4	Kitonga	1500	281	11	0.3	1.5	1.73 ± 0.10	0.67 ± 0.04	14.2 ± 0.9
Mean					0.2	2.0	1.42 ± 0.10	0.55 ± 0.02	24.2 ± 1.7

Table 3 The distribution of stand density, mean DBH and basal area across different elevations and DBH-size classes at Nyanganje and Kitonga Forest reserves, Eastern Arc Mountains, Tanzania

Plot no.	Forest type	Elevation (m)	DBH-size class (cm)	Stand density (stems ha^{-1})	Mean DBH (cm)	Basal area (m^2 ha^{-1})
1	Nyanganje	502	10–20	299	13.9 ± 0.3	4.7 ± 0.04
		502	21–30	52	24.6 ± 1.1	2.5 ± 0.03
		502	31–40	12	35.0 ± 1.9	1.2 ± 0.02
		502	41–50	11	45.4 ± 2.1	1.8 ± 0.05
		502	≥50	8	57.1 ± 2.8	2.1 ± 0.03
2	Nyanganje	791	10–20	237	14.6 ± 0.5	4.1 ± 0.03
		791	21–30	97	25.3 ± 0.7	4.9 ± 0.05
		791	31–40	37	35.0 ± 0.9	3.6 ± 0.05
		791	41–50	5	43.0 ± 0.1	0.7 ± 0.10
		791	≥50	0	0.0 ± 0.0	0.0 ± 0.00
3	Kitonga	1333	10–20	245	15.1 ± 0.5	4.6 ± 0.03
		1333	21–30	69	25.3 ± 0.7	3.5 ± 0.02
		1333	31–40	17	33.3 ± 0.9	1.5 ± 0.04
		1333	41–50	1	42.8 ± 0.0	0.1 ± 0.00
		1333	≥50	3	53.4 ± 1.7	0.7 ± 0.01
4	Kitonga	1500	10–20	236	13.9 ± 0.5	3.8 ± 0.03
		1500	21–30	38	24.0 ± 1.0	1.7 ± 0.04
		1500	31–40	6	35.6 ± 0.6	0.6 ± 0.06
		1500	41–50	1	43.2 ± 0.0	0.1 ± 0.00
		1500	≥50	0	0.0 ± 0.0	0.0 ± 0.00
Plot mean				344	18.1 ± 7.9	11.0 ± 0.01

tree species (29) at 1333 m and fewer trees species (11) at 1500 m in Kitonga. Shannon and Simpson indexes and the most dominant tree species were as shown in (Table 2 and Table 5) for each plot.

Wood density, tree and herb carbon stocks

Wood density for individual species ranged from 0.22 to 0.56 g cm^{-3}, with mean density of 0.39 ± 0.009 g cm^{-3}. The mean herbaceous dry mass and carbon density in the two forests were 1.42 ± 0.10 and 0.55 ± 0.02 Mg ha^{-1}, respectively (Table 2). The dry mass in the herb layer ranged from 0.98 ± 0.03 to 1.73 ± 0.10 Mg ha^{-1} in the higher elevation at Kitonga and 0.38 ± 0.02 to 0.67 ± 0.04 Mg ha^{-1} in the lower elevation at Nyanganje.

The Malimbwi, Solberg & Luoga (1994) and Abbot, Lowore & Werren (1997) volume models ranked the highest, while Brown *et al.* (1989) model ranked the lowest based on the above criteria (Table 1). The weighted mean carbon density value using the two models was 23.3 ± 9.8 Mg ha^{-1}, while the weighted mean for nine models combined was 23.4 ± 4 Mg ha^{-1}. We observed the highest carbon density at mid-elevation in Nyanganje and lowest carbon density at the highest elevation in Kitonga (Table 4). Mean carbon values derived from the nine allometric models ranged from 16.6 to 36.4 Mg ha^{-1} (Table 4). Estimates for the most dominant species at each elevation (Table 5) show that *Brachystegia bussei* Harms had the highest percentage carbon stock (18.3%) followed by *Brachystegia spiciformis* Benth. (16.5%), *Brachystegia longifolia* Benth. (11.7%) and *Uapaca kirkiana* Müll.Arg. (6%) accounting for 52.5% of the total stock, while the other 47.5% are from the remaining species.

Comparison with other estimates in the miombo eco-region

Results from this study (weighted mean of 23.3 Mg ha^{-1}) were slightly higher compared with results from Zahabu (2008), Chamshama Mugasha & Zahabu (2002) and Munishi *et al.* (2010), which were 22.5, 19.04 and 19.12 Mg ha^{-1}, respectively, from the same miombo vegetation type.

Table 4 Carbon stock values obtained from nine different models, which were used in carbon estimations at Nyanganje and Kitonga Forest Reserves in the Eastern Arc Mountains, Tanzania

	C (Mg ha^{-1}) Elevations (m)				
Reference model	502	791	1333	1500	Mean C (Mg ha^{-1})
Abbot, Lowore & Werren (1997)[a]	20.2	20.9	20.3	11.7	18.3
Malimbwi, Solberg & Luoga (1994)	19.1	20.6	16.5	10.0	16.6
Malimbwi, Solberg & Luoga (1994)[a]	37.8	39.1	23.5	12.9	28.3
Chamshama, Mugasha & Zahabu (2004)	31.1	32.0	24.0	13.1	25.0
Chave *et al.* (2005)	25.1	27.1	19.6	11.8	20.9
Brown *et al.* (1989)	30.6	32.5	24.7	14.1	25.5
Chidumayo (1990)	39.1	47.0	37.2	22.2	36.4
Frost (1996)	18.8	21.7	22.6	15.7	19.7
Chidumayo (1997)	29.3	36.0	28.2	16.0	27.4
Weighted mean Mg C ha^{-1}	27.3 ± 5.0	29.8 ± 5.9	23.06 ± 3.9	13.53 ± 2.3	23.2 ± 4

[a]Models with the highest ranking.

Table 5 Dominant species occurrence and the proportion of total carbon storage (%), carbon density (Mg ha^{-1}) distribution across different elevations at Nyanganje and Kitonga in Udzungwa and Kitonga mountains, Eastern Arc Forests, Tanzania

Plot no.	Forest type	Elevation (m)	Dominant species	Frequency	% Carbon density (Mg C ha^{-1})
1	Nyanganje	502	*Brachystegia bussei* Harms	163	18.3
		502	*Diplorhynchus condylocarpon* (Müll. Arg.) Pichon	83	2.6
		502	*Pterocarpus angolensis* D.C	24	2.4
		502	*Pseudolachnostylis maprouneifolia* Pax.	20	2.0
		502	*Burkea africana* Hook.	13	1.1
2	Nyanganje	791	*Brachystegia spiciformis* Benth.	149	16.5
		791	*Brachystegia bussei* Harms	40	3.9
		791	*Pseudolachnostylis maprouneifolia* Pax.	21	1.5
		791	*Burkea africana* Hook.	19	2.1
		791	*Brachystegia microphylla* Harms	18	1.7
3	Kitonga	1333	*Brachystegia longifolia* Benth	105	11.7
		1333	*Brachystegia spiciformis* Benth	49	4.3
		1333	*Julbernadia globiflora* (Benth) Troupin	77	4.1
		1333	*Brachystegia microphylla* Harms	2	0.8
		1333	*Faurea saligna* Harvey	10	0.6
4	Kitonga	1500	*Uapaca kirkiana* Muell.Arg.	123	6.0
		1500	*Brachystegia longifolia* Benth	69	5.3
		1500	*Julbernadia globiflora* (Benth) Troupin	58	2.6
		1500	*Parinari curatelifolia* Planch.ex Beth.	12	0.4
		1500	*Albizia antunesiana* Harms	4	0.2

Discussion

In this study, we have used field data collected from miombo woodlands in the EAM region of Tanzania, in combination with different allometric equations developed locally and more generally around the world to estimate AGBC in this vegetation type, which is the largest woody habitat in Tanzania.

Composition, structure, dominance and diversity

The tree density (344 stems ha^{-1}) and number of species observed in this study are lower than other studies in miombo woodlands for EAMs (Chamshama, Mugasha & Zahabu, 2004; Zahabu, 2008), which reported 460–1085 stems ha^{-1} and over 50 different species. This is because these studies included trees below 10 cm DBH. No other studies in the miombo woodland of Tanzania have used 10 cm DBH as minimum diameter in assessing carbon stocks. The high number of stems in the lower DBH class as compared to high DBH class and the usual J shape of the diameter distribution curve indicate good rates of regeneration (Philip, 1983; Isango, 2007). The low stocking of larger diameter trees classes in Kitonga compared with Nyanganje could be as a result of disturbance through selective harvesting for timber, charcoaling, pole cutting and possibly due to frequent fires under the past 'open-access' management regime for this woodland (Zahabu, 2008). Kitonga is currently in the final stage of gazettement to become a local authority forest reserve and suffers less harvesting pressure than in the past. Nyanganje has been a government Forest Reserve since 1958 and thus has been under a relatively strict management regime where harvesting is not allowed. The basal area for Nyanganje was comparable to other studies in Tanzania (Malimbwi, Luoga & Hassan, 2002). Although the basal area in Kitonga was lower, it was comparable to previous studies in the same site (Isango, 2007). This may indicate disturbance not only because of selective harvesting but also as a result of the study by Isango (2007) adopting a lower DBH limit. The difference between the two sites could also be owing to better growth conditions based on higher rainfall and better soils in Nyanganje, as compared with lower rainfall, poor soil and higher elevation in Kitonga.

Both forests are relatively diverse (Shannon index value: 1.05 and 1.25) in tree species compared with other studies in miombo (Nduwamungu, 1996; Luoga, 2000; Paré, 2008). Lower diversity indices in Kitonga compared with Nyanganje forests may indicate different environmental factors, levels of disturbance or stochastic variation because of limited sample sizes. In terms of tree species richness, Kitonga appears to be richer possibly not only because of environmental and edaphic influences but also because of the disturbance regime. It has been argued that the relationship between species diversity/richness and disturbance is hump-shaped with highest species diversity and/or richness at intermediate levels of disturbance (Connell & Slatyer, 1977; Haddad *et al.*, 2008).

Wood density, tree and herb carbon stocks

The average wood density reported here (0.39 ± 0.009 g cm^{-3}) was lower than in other studies in miombo woody savannah. Malimbwi, Solberg & Luoga (1994) reported mean wood density of 0.66 g cm^{-3} for miombo in Kitualanghalo Tanzania, and Williams *et al.* (2008) reported mean wood density of 0.57 g cm^{-3} for heartwood and 0.55 g cm^{-3} for sapwood in miombo trees from Mozambique, averaging 0.56 g cm^{-3}. However, in the present study, wood density was not measured in sapwood and heartwood separately because of differences in methods used, which may have led to different results. The wood density of different species may be affected by site-specific growth conditions and age differences in succession changes as well as position on the tree (Williams *et al.*, 2008). However, the difference between heart wood and sapwood as well as the age effect on wood density was not addressed in this study.

Miombo woodlands, like other vegetation types, have spatial carbon storage variability because of variations in growth conditions and possibly species composition. However, differences in approaches to data collection like the use of larger (1 ha) plot, analysis techniques such as the use of several allometric models and different micro-climates at different sites could be the cause of this variation. According to Brown (2003), equations used in carbon estimates can result in different outputs depending on input variables, vegetation type and geographical location from which the model was originally developed. Although we found out that the two allometric equations (Malimbwi, Solberg & Luoga, 1994 and Abbot, Lowore & Werren, 1997) were ranked high, they have different outputs because of different input variables used. We found out that Nyanganje at lower elevation had higher carbon density than Kitonga, which could be owing to variations in rainfall, edaphic factors, management regimes, disturbance levels or stochastic variation because of small sample size. Generally, despite these differences, the carbon density observed in this study falls within the range that has been reported in other studies for miombo woodlands in Tanzania (Malimbwi, Solberg & Luoga, 1994; Munishi *et al.*, 2010).

The estimated biomass of 1.42 ± 0.10 Mg ha^{-1} in this study for the herbaceous layer is closely comparable to estimates by Rutherford (1982) in South African savannah (1.5 Mg ha^{-1}), Rushworth (1978) in Zimbabwean savannah (*Terminalia sericea* woodlands) (1.23 Mg ha^{-1}) and Rajvanshi & Gupta (1985) in drought deciduous forest in India (1.33 Mg ha^{-1}). Values of biomass and carbon stocks in Kitonga forest are relatively higher compared with Nyanganje woodland, which may be owing to differences in site growth conditions and tree canopy cover. It has been argued that herbaceous biomass and carbon in tropical savannah ecosystem have been said to be influenced by rainfall, temperature and soil characteristics, herbivory, fire and anthropogenic activities (Walter, 1971; Belsky, 1989; San Jose & Montes, 2007; Kangalawe, 2009). The canopy was more closed in Nyanganje than Kitonga woodland because of differences in rainfall and temperature, which varies with altitude in the EAMs.

Comparison with other miombo eco-region estimates

Miombo woodlands store significantly less AGBC (23.3 Mg C ha^{-1}) compared with closed-canopy evergreen forests in Africa, which are estimated to store an average of 200 Mg C ha^{-1} (CI, 174-244) (Lewis *et al.*, 2009). However, Munishi & Shear (2004) reported over 300 Mg C ha^{-1} carbon stock in the Eastern Arc afromontane forests. Miombo woodland vegetation covers about 45% of the Tanzanian land surface, compared with about 2% of closed-canopy forest (Rodgers, 1996; Ministry of Natural Resources and Tourism, 1998). Thus, miombo woodland are a more important store of carbon than tropical forests in Tanzania given their extensive coverage. A comparison with other studies outside the EAM indicates that observed carbon density could range from 11 to 24 Mg ha^{-1}. The estimates in this study may provide useful input into the current REDD initiatives in Tanzania and globally as they provide a detailed field-based estimate of carbon storage within the miombo woodland eco-region. These data are essential to measure the impact of policy interventions to reduce degradation and deforestation and therefore calculate future carbon storage, against which payments can be made. However, extensive on-the-ground sampling coupled with remote sensing products is necessary to improve the accuracy of the estimates.

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