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Carbon storage and emissions offset potential in an African dry forest, the Arabuko-Sokoke Forest, Kenya

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Abstract Concerns about rapid tropical deforestation, and its contribution to rising atmospheric concentrations of greenhouse gases, increase the importance of monitoring terrestrial carbon storage in changing landscapes. Emerging markets for carbon emission offsets may offer developing nations needed incentives for reforestation, rehabilitation, and avoided deforestation. However, relatively little empirical data exists regarding carbon storage in African tropical forests, particularly for those in arid or semi-arid regions. Kenya's 416 km^2 Arabuko-Sokoke Forest (ASF) is the largest remaining fragment of East African coastal dry forest and is considered a global biodiversity hotspot (Myers et al. 2000), but has been significantly altered by past commercial logging and ongoing extraction. Forest carbon storage for ASF was estimated using allometric equations for tree biomass, destructive techniques for litter and herbaceous vegetation biomass, and spectroscopy for soils. Satellite imagery was used to assess land cover changes from 1992 to 2004. Forest and thicket types (*Cynometra webberi* dominated, *Brachystegia spiciformis* dominated, and mixed species forest) had carbon densities ranging from 58 to 94 Mg C/ha. The ASF area supported a 2.8–3.0 Tg C carbon stock. Although total forested area in ASF did not change over the analyzed time period, ongoing disturbances, quantified by the basal area of cut tree stumps per sample plot, correlated with decreased carbon densities. Madunguni Forest, an adjoining forest patch, lost 86% of its forest cover and at least 76% of its terrestrial carbon stock in the time period. Improved management of wood harvesting in ASF and rehabilitation of Madunguni Forest could substantially increase terrestrial carbon sequestration in the region.

Keywords Africa · Carbon storage · Arabuko-Sokoke Forest · Dry coastal forest · Forest management · Kenya · Land cover change

Introduction

Dry forest is the most widely distributed habitat type in the tropics (Jaramillo et al. 2003), covering 42% of all tropical vegetation (Murphy and Lugo 1995). While dry forests typically have lower biomass densities than wetter forests, their extensive coverage makes them a significant terrestrial carbon store. Conversion of African dry forest to agricultural usage dramatically reduces ecosystem carbon stocks (Woomer 1993). As carbon emissions from land cover change have been linked with increasing global

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concentrations of greenhouse gases (Brown 1997; Houghton 1997; Clark and Clark 1999), the importance of monitoring terrestrial carbon storage has grown. An estimated 13 million ha of tropical forest is lost each year to deforestation (FAO 1999), emitting 5.6–8.6 Gt of heat-trapping carbon into the atmosphere. Tropical dry forest has been cleared or degraded in larger proportions than moist forest (Mooney et al. 1995; Jaramillo et al. 2003).

Biomass models for Africa have suggested that much of the land biophysically suited for forest cover has been degraded and deforested and that Kenya, among other nations, could almost double its aboveground biomass (Brown and Gaston 1995; Zhang and Justice 2001). Kenya has struggled to preserve its forests and lost 930 km^2 of closed forest in the past decade (FAO 1999). East Africa's coastline once supported a continuous belt of dry coastal forest from southern Somalia to northern Mozambique, but this has largely been cleared and the remaining fragments have been subject to intensive selective logging (Burgess and Clarke 2000). Emerging global markets for carbon credits, accrued from activities that offset or reduce carbon emissions, could provide incentive for rehabilitation and sustainable forest management in this threatened ecosystem.

The Arabuko-Sokoke Forest (ASF) of Kenya is the largest remaining fragment of East African coastal dry forest. An internationally recognized biodiversity hotspot, ASF ranked eighth in the world for biodiversity and first for density of endemic species (Myers et al. 2000). While ASF is now legally protected, the effects of past commercial logging operations and continued extractive use impact forest structure (Robertson and Luke 1993; Fanshawe 1995; Wright 1999). This study aims to estimate carbon densities for ASF forest types and provide a preliminary assessment of the potential to increase carbon storage in the area.

Methods

Site description

The Arabuko-Sokoke Forest (3°20′ S, 39°50′E) is located in Kenya's Coast Province, lying in both Malindi and Kilifi Districts. The officially delineated ASF area covers roughly 416 km^2, with 382 km^2 of indigenous forest. The northeastern side of the forest borders the shores of Mida Creek at sea level. Elevation increases westward, with a steep climb from the eastern coastal plain (0–45 m above sea level) to a plateau (60–135 m) in the central and western parts of the forest reaching a peak of 210 m in the southwest. Rainfall varies across the elevation gradient with the eastern, coastal edge receiving 1,000–1,100 mm/year and northwestern forest receiving 600–900 mm/year. A mean daily temperature of 25°C and high humidity fluctuate little throughout the year.

ASF supports three distinctive and well-described forest types (Kelsey and Langton 1984; Mutangah and Mwaura 1992; Robertson and Luke 1993; Fanshawe 1995; Muchiri et al. 2001), associated with soil types, precipitation regimes, and altitudes. *Cynometra* forest and thicket occur on the drier western ridge on deep, leached, red soils. This dense forest has a canopy (5–20 m) dominated by *Cynometra webberi,* commonly occurring with *Manilkara sulcata*, *Oldfieldia somalensis* and, before intensive harvesting, *Brachylaena huillensis*. *Brachystegia* forest grows on a band of white, infertile sand running through the center of ASF where well-spaced, tall (20 m), deciduous *Brachystegia spiciformis* trees create a loose canopy over a shrub understory. Patches of *Brachystegia* forest also occur on eroded sandy valley bottoms on ASF's western edge. Mixed forest, in which a variety of tree species, notably *Combretum schumannii*, *Drypetes reticulata*, *Afzelia quanzensis*, *Dialium orientale*, *Hymenaea verrucosa*, and *Manilkara sansibarensis*, form a tall (15–20 m) closed canopy, occurs on the wetter, eastern coastal plain on grey colored Pleistocene lagoonal sands and clays. A mixed species (*M. sulcata*, *B. hulliensis*, and *Strychnos madagascariensis*) short thicket (3–8 m) occurs on silt soil on the dry northwestern edge and open grasslands occur near forest pools and previously cleared areas.

While surrounding areas have largely been deforested (Kelsey and Langton 1984; Ngala 2004), the ASF protected area has maintained forest cover despite significant extractive use. ASF was declared a Forest Reserve in 1943. Although initially managed for commercial timber harvest of valuable indigenous hardwoods, such as *Brachylaena huillensis, Afzelia quanensis,* and *Manilkara sansibarensis*, by the 1970's stocks were too depleted to support commercial sawmills. In 1968, 2,700 ha in the center of the forest was declared a Nature Reserve in which no extractive use was permitted. Logging in all Forest Reserves was nationally banned in 1982 and fuelwood collection in 1999, however illegal tree felling for both subsistence uses (fuelwood, poles) and commercial uses (timber, furniture, carvings) have continued in ASF at potentially unsustainable levels (Kelsey and Langton 1984; Wright 1999; ASFMT 2002).

ASF has more recently been co-managed for conservation and tourism by Kenya Wildlife Service, Forest Department, Kenya Forest Research Institute, National Museums of Kenya, and Nature Kenya. A pilot participatory forest management system was initiated in 2004 in the Dida sublocation on the west side of the forest. Sustainable harvest and monitoring plans were to be researched and negotiated with forest adjacent dwellers' associations, allowing for limited subsistence resource extraction from demarcated forest edge zones (Mbuvi et al. 2004).

The Madunguni Forest was also included in the study area. It is an 860 ha area containing *Cynometra* forest and thicket directly abutting the northern edge of ASF. Madunguni was managed as a County Council Forest until November 2004 when it was declared a reserve to be managed by the Forest Department.

Carbon storage inventory plots

Carbon stocks were measured in 6 pools (tree aboveground biomass, tree belowground biomass, coarse deadwood ≥10 cm diameter, litter, herbaceous vegetation, and soil) in 97 circular, 20 m-radius (0.126 ha) inventory plots (Brown 1997; MacDicken 1997). Plots were randomly located within mapped areas of major forest types (ASFMT 2002) with 6 plots located in Madunguni Forest. Plot positions and sites of timber or fuelwood cutting were recorded using a GPS unit (Garmin, GPS II Plus).

Diameter at breast height (1.3 m), dbh, was measured for standing trees and lianas in nested concentric subplots: ≥5 cm dbh in a 4 m radius, ≥20 cm dbh in a 14 m radius, ≥40 cm dbh in a 20 m radius. Tree aboveground biomass (AGB) was estimated from dbh using a generalized tropical dry forest equation (Brown 1997). Belowground biomass (BGB) was calculated from AGB as in Cairns et al. 1997. It was assumed that 50% of vegetative biomass was carbon.

The mass of coarse deadwood on the ground was estimated in each plot by measuring diameters and decomposition status of all downed trees and branches with diameter≥10 cm along two perpendicular 40 m transects. The density of lying deadwood was calculated using Harmon and Sexton's (1996) method and decomposition class data reported for dry forest conditions by Jaramillo et al. (2003). The mass of standing dead trees was estimated using the same biomass equations as live trees but discounted by damage classes based on remaining twigs and branches as described in Pearson et al. (2005). The diameter at ground level (dgl) of tree stumps in the plot were measured in the same manner as live trees and stump surface area per hectare at ground level was calculated to indicate disturbance intensity.

Within inventory plots, four 0.5×0.5 m subplots were established in which all understory vegetation was removed and weighed. Litter was also collected in each subplot. Two hundred gram herbaceous and litter subsamples were oven-dried to calculate wet–dry weight ratios and estimate total sample mass.

Soil cores were taken with a tube corer to a depth of 30 cm and separated into 10 cm depth intervals. Samples were air-dried, sieved to 2 mm, weighed for bulk density, and pulverized. Carbon concentrations were predicted using a spectral library approach (Shepherd et al. 2002) using diffuse reflectance spectroscopy (FieldSpec FR spectroradiometer; Analytical Spectral Devices, Boulder, CO, USA) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm (Shepherd et al. 2003). Soil carbon was measured on a random selection of 15% of the samples by acid oxidation and sampled carbon concentrations were calibrated to reflectance spectra using partial least squares regression with Unscrambler 7.5© software (CAMO, Corvallis, OR, USA). Regression models were used to predict concentrations from spectra for the remaining samples. Soil carbon density was calculated as carbon concentration multiplied by bulk density and sample depth.

Plots were classified into the three major forest types on the basis of calculated species importance values (Brower et al. 1998), surrounding forest, and soil type. Post sampling, an effort was made to divide general forest types into subclasses with distinct carbon densities: *Cynometra* and mixed forest plots were placed in 'thicket' subclasses if plots had canopy heights ≤10 m, had more than 90% of trees with dbh

≤20 cm, or were found in areas identified as ‘thicket’ in previous studies (Kelsey and Langton 1984; ‘other vegetation’ in ASFMT 2002). Plots satisfying all criteria were considered ‘thicket.’ Plots satisfying two criteria were classified based on size distributions. Northwestern thicket plots in the area previously identified as ‘impenetrable thicket’ or ‘other vegetation’ (ASFMT 2002), were classed as ‘other thicket.’ Plots located in known areas cleared in the 1930s to 1960s for sawmill camps and sand mines were considered ‘regenerating.’

Mapping forest cover to estimate carbon stock

The area covered by forest and open cover types was estimated from spectral analyses of Landsat satellite images (*scene*: 166/62, *images*: 24/6/1992 from Landsat TM, 29/9/2004 from L7 ETM). Land cover classification was performed using the “maximum likelihood function” in ENVI 4.1 on Landsat images (copyright Research Systems, Inc., USA) using ground-truthed GPS points as spectra ‘training classes.’ The Jeffries–Matusita separability index was used to estimate the spectral differences between training class areas of assumed different cover types. Training pixels were chosen and cover classes were accepted to achieve separability index values ≤1.95 between all cover types. A second set of ground-truthed points was used to determine map accuracy. Average carbon densities for sampled vegetation types were multiplied by their estimated coverage to estimate carbon stock.

Statistics and uncertainty assessment

One-way ANOVA was used to detect statistically significant differences between carbon density averages amongst forest types. Pair-wise comparisons between classes were made using Student’s *t*-tests, or Tukey’s HSD test in cases where data had a significantly non-normal distribution. Unless otherwise indicated, an alpha of 0.05 was used for significance tests. In tropical forest inventories, measurement uncertainties generally contribute an insignificant amount to overall uncertainty of estimated mean carbon densities when compared to uncertainty introduced by natural variations between individual plots of one forest type (Chave et al. 2003, Keller et al. 2001, Brown et al. 1995). Therefore only sampling error was included in the 95% confidence interval (±95%CI) estimates presented for all mean values.

Results

Forest carbon density

Mean *total* carbon densities for broad forest types *Brachystegia* forest (80±6 Mg C/ha), *Cynometra* forest/thicket (74±6 Mg C/ha), and mixed forest (77± 12 Mg C/ha), were not statistically significantly different from each other. However, carbon densities for tree biomass and soil pools were significantly different across forest types (Table 1). *Brachystegia* forest had the highest tree AGB carbon (46±5 Mg C/ha), significantly higher than *Cynometra* (35±5 Mg C/ha), but the lowest soil carbon (13±1 Mg C/ha), significantly lower both than *Cynometra* (24±2 Mg C/ha) and mixed forest (21±4 Mg C/ha). *Brachystegia* had the highest herbaceous carbon (0.46±0.3 vs 0.06–0.07 Mg C/ha in the other types. *Cynometra* had the lowest coarse deadwood (1.1±0.2 vs 1.8–1.9 Mg C/ha) and litter (1.8±0.2 vs 3.3–4.6 Mg C/ha).

Among *Cynometra* plots, mean total carbon density for the ‘forest’ subclass (83±8 Mg C/ha) was significantly greater than ‘thicket’ (65±6 Mg C/ha) and ‘regenerating’ (35±12 Mg C/ha). *Cynometra* subclasses all had similar soil carbon, but AGB carbon density in forest plots was significantly higher than thicket by 14 Mg C/ha and regenerating by

Table 1 Forest carbon density and distribution amongst carbon pools in major forest types of Arabuko-Sokoke Forest

Carbon pool	Forest type mean carbon density		
	(Mg C/ha±95% confidence interval)		
	Brachystegia	*Cynometra*	Mixed
Aboveground tree biomass	46±5	35±5	38±8
Belowground tree biomass	12±1	10±1	14±3
Deadwood biomass	3.4±1.2	3.7±1.	62.4±1.6
Soil carbon	13±1	24±2	23±7
Herbaceous biomass	1.8±0.9	0.07±0.04	1.7±1.4
Litter biomass	4.3±1.1	1.8±0.2	3.3±0.9
Total mean carbon density	80±6	74±6	78±12

33 Mg C/ha. Among mixed forest plots, mean total carbon density for the ‘tall mixed forest’ subclass (94±16 Mg C/ha) was significantly greater than ‘thicket’ (64±11 Mg C/ha) and ‘regenerating’ (51±37 Mg C/ha, $p<0.1$). Tall forest had significantly more AGB carbon than thicket by 14 Mg C/ha and significantly more soil carbon than regenerating areas by 12 Mg C/ha. Mixed thicket and tall forest had similar soil carbon densities (22±6, 23±7 Mg C/ha), but regenerating areas had lower soil carbon than both forest and thicket. It was not possible to map the regenerating areas in this study, so regenerating plots were included in the other subclass mean carbon density estimates used to calculate ASF total carbon stock (Tables 2, 3 and 4).

Splitting forest types into subclasses increased class carbon separability, allowing for more detailed carbon stock and carbon distribution estimation. Tall mixed forest had the highest total carbon density of all types, significantly higher than *Brachystegia* forest, all thicket types (*Cynometra*, mixed, and other), and all regenerating areas. *Cynometra* ‘thicket’ and mixed ‘thicket’ differed in species composition and soil type, but had almost the same total carbon density (65±6 vs 64±11 Mg C/ha) and contributions from trees (AGB 24±5 vs 27±8 Mg C/ha) and soils (22±3 vs 22±6 Mg C/ha). The ‘other thicket,’ despite having higher soil carbon, had the lowest total carbon density (58±3 Mg C/ha) of thicket classes due to low AGB. The highest AGB values of all plots in the study (90–100 Mg C/ha) were seen in the transitional areas between *Brachystegia* and other forest types in which large *B. spiciformis* trees were interspersed with other forest trees.

Table 2 Forest carbon density and distribution of carbon amongst carbon pools in subdivisions of the *Cynometra* forest type

Carbon pool	Forest type mean carbon density		
	(Mg C/ha±95% confidence interval)		
	Cynometra forest	*Cynometra* thicket	‘Other’ thicket
Aboveground tree biomass	42±6	28±5	23±8
Belowground tree biomass	12±2	8±1	7±2
Deadwood biomass	3.2±2.0	4.7±2.9	2.9±4.6
Soil carbon	25±2	22±3	24±3
Herbaceous biomass	0.10±0.14	0.02±0.02	0.00±0.00
Litter biomass	1.5±0.2	2.3±0.5	1.7±1.4
Total mean carbon density	83±8	65±7	58±3

Table 3 Forest carbon density and distribution of carbon amongst carbon pools in subdivisions of the mixed forest type

Carbon pool	Forest type mean carbon density	
	(Mg C/ha±95% confidence interval)	
	Mixed forest – tall	Mixed forest – thicket
Aboveground tree biomass	50±11	27±8
Belowground tree biomass	14±3	7±2
Deadwood biomass	3.8±1.9	3.8±2.8
Soil carbon	23±7	22±6
Herbaceous biomass	0.04±0.02	0.03±0.02
Litter biomass	3.5±1.3	3.4±1.1
Total mean carbon density	94±16	64±12

Evidence of recent felling of medium to large trees (dbh≥20 cm) was observed in all three major forest types and did affect carbon density. ‘Old’ stumps were most frequently observed in *Cynometra* forest and thicket plots (88%, 83%), while ‘recent’ cutting was most frequently observed in mixed thicket plots (56%) and *Cynometra* forest (24%). Plots with fresh stumps had significantly less carbon than plots without stumps in both mixed forest (34 Mg C/ha less) and *Cynometra* forest (16 Mg C/ha less). Old stumps were too widespread to make significant comparisons; however, in the absence of new stumps, plots with old stumps generally had lower carbon densities. Regression analyses of stump surface area and plot AGB carbon densities showed a negative relationship between disturbance intensity and carbon within all forest sub-classes; however, the relationships were weak (all $r^2<0.4$) and statistically insignificant (all $p>0.1$) at this sampling intensity. Systematic sampling across a range of disturbance intensities would be needed to establish any quantifiable relationship.

In general, recent cutting of *small* trees and branches (3–20 cm), presumably for fuel and pole-wood, occurred around forest edges and was more

Table 4 2004 estimate of land cover and carbon stocks for the Arabuko-Sokoke Forest based on spectral classification of satellite images

Forest type	Carbon density (Mg C/ha±95%CI)	Area (ha)	Carbon stock (Tg C± 95%CI)
Broad forest types			
Brachystegia	79.7±6.2	7,714	0.62±0.05
Cynometra	73.7±6.0	25,621	1.89±0.15
Mixed forest	77.7±12	7,140	0.56±0.09
Total		40,476	3.07±0.18
Forest subclasses			
Brachystegia	79.7±6.2	7,714	0.62±0.05
Cynometra forest	83.4±7.7	12,157	1.01±0.09
Cynometra thicket	64.9±6.5	11,334	0.74±0.07
Mixed forest – tall	94.2±15.9	3,530	0.33±0.06
Mixed forest – thicket	63.9±11.4	3,610	0.23±0.04
Other thicket	57.7±1.3	2,130	0.12±0.00
Total		40,476	3.05±0.15

commonly observed than cutting of larger trees in all types, but an influence on carbon density was not detected in the sample. A consistent trend of lower mean carbon density with harvesting than without cutting was observed across all types. All types of recent extraction were seen with greater frequency in the Madunguni *Cynometra* (100% of plots), than in ASF's *Cynometra* (33%) (Fig. 1).

Land cover maps and cover change

Spectral analyses of Landsat images (Fig. 2, Table 4) were able to differentiate between the *Brachystegia*, *Cynometra*, mixed forest, and 'other thicket' with an accuracy of 95%. Mismatched field and map classifications occurred for plots at the edge of two forest types and for plots with patches of bare ground, which were classified as shrubland or other thicket. Accuracy decreased to 75% when mapping separate thicket and forest subclasses. Field based differentiation between thicket and forest did not strongly correspond to spectral differences in the images and Jeffries–Matusita separability indices were low (1.90–1.92). Mapping *Cynometra* thicket and forest classes showed higher map user's and producer's accuracies (80–87%) than mixed thicket and tall forest (50–67%).

While there was no notable change in forest cover in the ASF area between 1992 and 2004, the Madunguni Forest lost roughly 86% of its forest cover over this period (Fig. 3, Table 5). Image classification suggested the area had roughly 780 ha of *Cynometra* thicket/forest and *Brachystegia*-like woodland in 1992, but 670 ha became open fields or shrubland over 12 years.

Carbon stock

Total carbon stock for ASF was found to be 2.8–3.0 Tg C (Table 4). Using the most basic forest classification (*Brachystegia*, *Cynometra*, mixed forest)

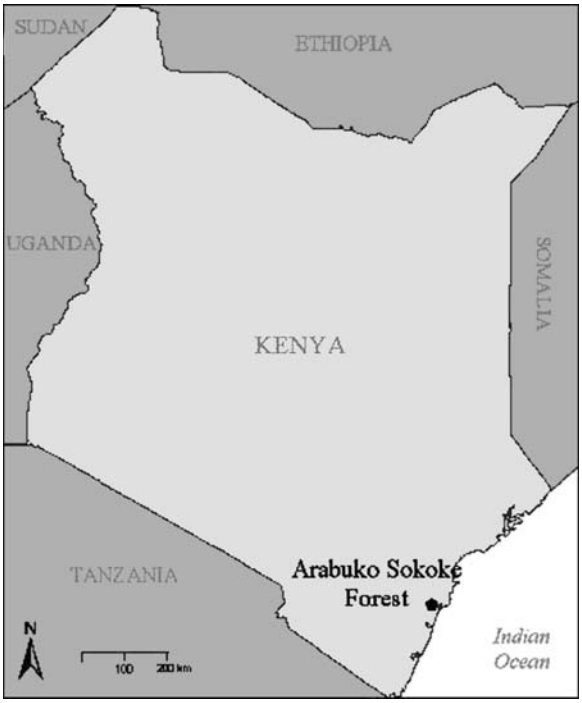

Fig. 1 Location of Arabuko-Sokoke Forest

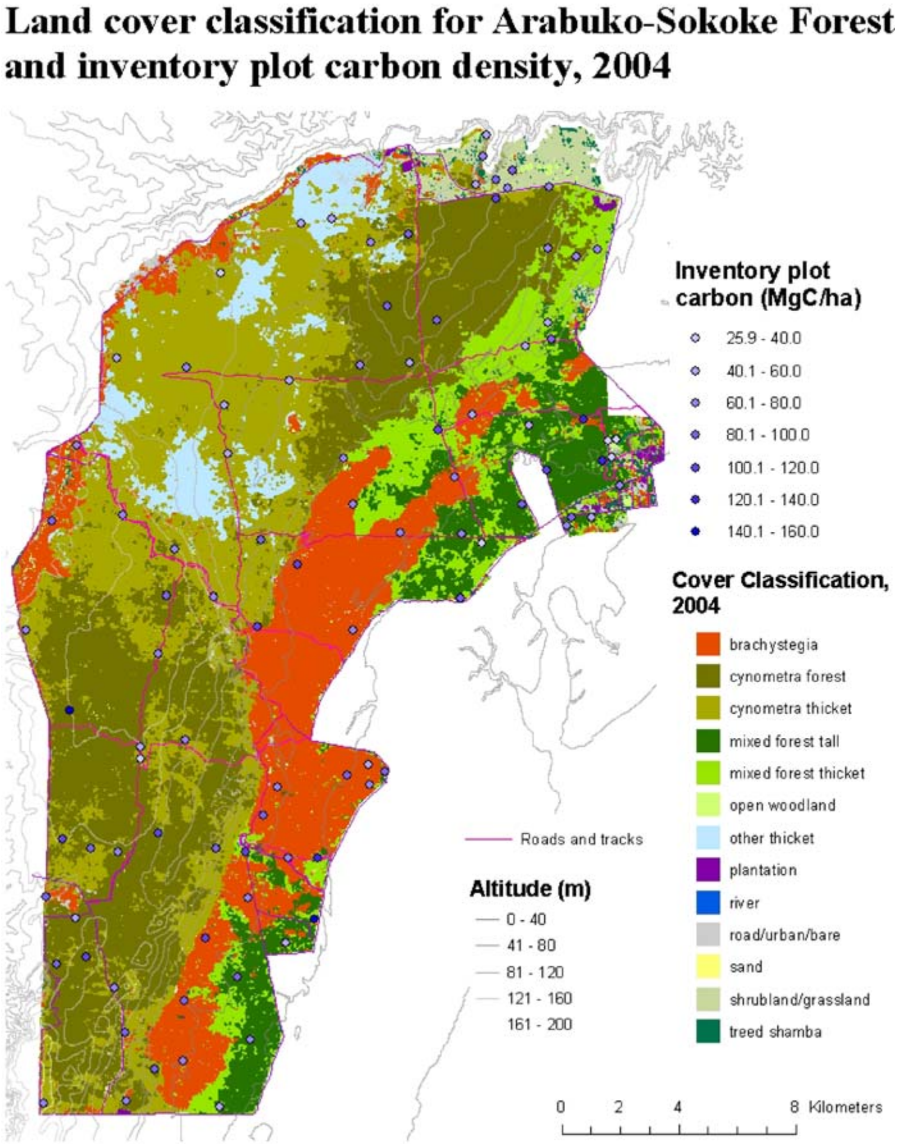

Fig. 2 Land cover and inventory plot locations. Map resulting from supervised spectrally based classification of a Landsat image (L7 ETM, 166/62, 29/9/2004) after clumping isolated pixels. Inventory plot locations based on GPS readings. Madunguni Forest is included in the north of ASF

yielded a 3.07±0.18 Tg C stock. Splitting forest types into subclasses did not produce sizeable differences in total stock when compared to estimated uncertainty levels, but using subclasses did narrow the confidence interval of the estimate. Separating thicket and forest subclasses decreased both the stock estimate and the confidence interval by 0.02 Tg C.

To make a conservative approximation of the carbon stock change in Madunguni Forest, the following assumptions were made: only tree AGB and BGB changed significantly in the 1992–2004 time period; AGB carbon densities in non-treed land cover types were relatively insignificant; and open canopy treed cover types, treed shambas (small farms) and open woodlands, had carbon densities similar to published data for miombo woodlands (19 Mg C/ha, Woomer 1993), an open canopy vegetation type found in similar temperature and rain conditions. Using these assumptions, Madunguni lost roughly 20,000 Mg C (76%) from 1992 to 2004.

Discussion

Carbon density values estimated for ASF forest types fit into the range of estimates for other dry tropical

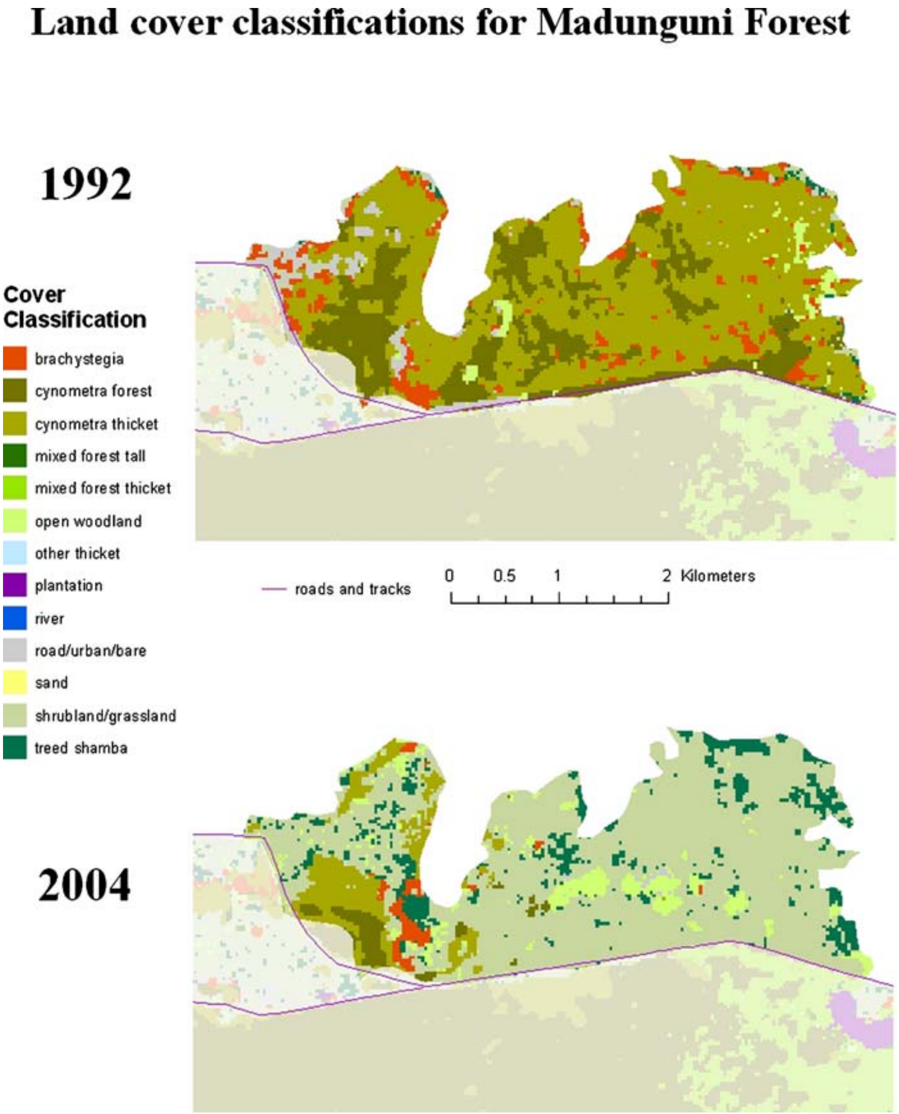

Fig. 3 Land cover classification and change for Madunguni Forest 1992–2004. Map resulting from supervised spectrally based classification of a Landsat images (166/62; 24/6/92 TM, 29/9/2004 L7 ETM) after clumping isolated pixels. Madunguni Forest abuts the north end of the Arabuko-Sokoke Forest

forests and greater than estimates for other dry vegetation types, open savanna and woodlands. AGB carbon estimates in ASF mature forest classes (23–50 Mg C/ha) were close to values predicted by biomass models for actual and potential AGB carbon densities in African dry forests (30–46 Mg C/ha; Brown and Gaston 1995). ASF values were also similar to estimates from field studies in dry forests in Thailand (48 Mg C/ha; Owaga et al. 1965), Belize (39 Mg C/ha, Lambert et al. 1980), Puerto Rico (22 Mg C/ha), and Mexico (41 Mg C/ha; Martinez-Yrizar et al. 1992; 35 Mg C/ha; Jaramillo et al. 2003).

ASF biomass estimates were consistent with other dry forests, but its soil carbon densities (22–25 Mg C/ha in all types) were lower than other published values: 45–50 Mg C/ha lower than estimates for soils in South African savanna and Mexican dry forests (Woomer 1993; Jaramillo et al. 2003). However, forest soil carbon densities were higher than agricultural soils in adjacent areas (8–14 Mg C/ha; Mchua and Lelon 2004) indicating carbon losses on cultivation. ASF soil estimates were consistent with Zimbabwean miombo woodland soils (21 Mg C/ha; Woomer 1993). Despite similar soil carbon and species composition, closed canopy ASF *Brachystegia* forest (46±5 Mg C/ha) had more than twice the AGB carbon of open miombo woodland (19 Mg C/ha; Woomer 1993).

While total ASF carbon stock could be more precisely quantified with improved accuracy in mapping forest types with distinct carbon densities

Table 5 Estimated land cover and carbon stock change for Madunguni Forest 1992–2004 based on spectral classification of satellite images

Cover type	AGB carbon density	1992		2004		Change 1992–2004	
	(Mg C/ha±95%CI)	Area (ha)	AGB carbon stock (Mg C/ha±95%CI)	Area (ha)	AGB carbon stock (Mg C/ha±95%CI)	Area (ha)	AGB carbon stock (Mg C/ha±95%CI)
*Brachystegia**	46±5	65	3,000±330	15	700±80	−50	−2,300±330
Cynometra forest	42±6	190	8,060±1,150	20	860±120	−170	−7,200±1,160
Cynometra thicket	28±5	520	14,610±2,610	72	2,000±360	−448	−12,600±2,630
Treed shamba	19±2	6	110±10	85	1,610±170	79	1,500±170
Open woodland	19±2	20	370±40	58	1,100±110	38	730±120
Road/bare	N/m	37	N/m	0	N/m	−37	N/m
Sand	N/m	0.4	N/m	3	N/m	3	N/m
Shrub/ grassland	N/m	13	N/m	600	N/m	590	N/m
Grass	N/m	0	N/m	0.1	N/m	0	N/m
Forested area		780		100		−670	
Total		860	26,000±2,900	860	6,300±440		−20,000±2,900

N/m: not measured

such as *Cynometra* forest vs thicket or disturbed vs undisturbed, the variation in carbon densities detected clearly indicate potential to increase terrestrial carbon stocks within protected areas by preventing further forest degradation and promoting rehabilitation of the Madunguni Forest area. Although observed carbon densities fell into an expected range of values, observations suggest that past and ongoing disturbances have reduced carbon stocks below potential. The ASF area is still recovering from its history of commercial logging. Old cut stumps of *B. hullensis* and *A. quanzensis* were observed with dbh values over 50 cm, while only one of the living trees measured exceeded 40 cm.

Given a chance to regenerate, it appeared the forest could achieve a greater average carbon density; however, the level of ongoing and widespread forest use has notably reduced forest carbon density, slowing or preventing recovery. Increasing net carbon storage in the area will entail sustainable wood harvesting plans accompanied by tree-planting activities outside ASF to address fuel and wood needs of local communities. Evidence of fuelwood cutting did not clearly correlate with the lower carbon densities at this sampling intensity, but with the slow growing nature of dry forest hardwoods and the growing population around the forest, it is possible the cutting of small trees and branches may exceed growth. Felling of medium to large trees more clearly reduced forest carbon stocks. While some of the wood from these larger trees is used for carving and building materials, uses which don't create direct carbon emissions like burned fuelwood, using woodlots to address these needs would provide extra carbon storage as well as protecting ASF. As tree felling is an illegal activity that proceeds due to need and ineffective enforcement, there was no accurate data on volumes extracted or end-uses.

Because so few areas were found to be undamaged, it is difficult to accurately speculate what the carbon density the forest types could reach if allowed to regenerate. The few plots lacking evidence of cutting had AGB carbon densities 10–20 Mg C/ha higher than cut plots for *Cynometra* forest and mixed forest. If this sample does represent the sequestration potential from forest recovery, 100–200 thousand Mg C additional sequestration across ASF could be possible with improved forest management. While growth rates for these forest types have not been studied, a rough estimation of 0.28 Mg C/ha/year based on the accumulation of 11±6 Mg C/ha in tree biomass in *Cynometra* plots cleared 40 years ago for the Dida sawmill, indicates that it would take 35 years or more for ASF to sequester 100 thousand Mg C. Assuming the Madunguni area could be rehabilitated to its 1992 cover with at least the AGB density seen in ASF *Cynometra*, it may also be possible to sequester 20,000 Mg C or more through reforestation activities.

Conclusion

The rapid degradation of many carbon-storing vegetation types across the tropics is both exacerbating global climate change and contributing to the loss of natural resources and ecosystem services that communities depend on. Dry forests, while they generally store less carbon than wetter forests, cover greater areas in the tropics and are generally more degraded, making them key areas to target terrestrial carbon storage recovery and prevented deforestation projects. Such projects could also help preserve biodiversity and maintain ecosystem services. Like many forest reserves in the tropics, Kenya's Arabuko-Sokoke Forest is influenced by complex human-resource requirements. ASF and the adjoining Madunguni Forest provide examples of protected areas of East African coastal dry forest that could noticeably and feasibly increase their carbon stocks with rehabilitation and improved management.

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