

**A Preliminary Assessment of Carbon Storage and the Potential for Forestry
Based Carbon Offset Projects in the Kakamega National Forest, Kenya**

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Abstract

Forestry based carbon offset projects have the potential to act as both a climate change mitigation tool and a means of fostering sustainable forest preservation. While modeling has provided positive assessments of the potential for African tropical forests to sequester large amounts of carbon, the lack of localized field studies has limited the feasibility of initiating biotic carbon emissions offset projects in many of the continents threatened forests. This study provides an analysis of carbon storage and the potential to increase carbon stocks in the Kakamega National Forest of western Kenya, a threatened African rainforest fragment. Such an assessment is required by Kenya's commitments under the United Nations Framework Convention on Climate Change and as a baseline for participation in the Clean Development Mechanism of the Kyoto Protocol to the convention.

Carbon density values for indigenous forest and plantations were estimated based on data collected in ninety five randomized 20x20m plots throughout the Kakamega National Forest from June to August of 2003. Tree biomass was estimated from diameter at breast height (dbh) measurements and allometric equations, while litter and herbaceous vegetation biomass was quantified using destructive sampling. Soils were sampled using both combustion and spectroscopy techniques. Land cover maps for 1975, 1986, and 2000 from Kenya's Department of Remote Sensing and Resource Surveys (DRSRS), were used to estimate both current carbon storage in the forest and the influence of land use change over the past 25 years on forest carbon stocks.

The average carbon storage density in indigenous forest is 330 ± 65 Mg C/ha (95% confidence interval), which is greater than that of the average found in the forest's hardwood plantations (280 ± 77 Mg C/ha) and significantly greater than that of softwood plantations (250 ± 77 Mg C/ha). Deforestation between 1975 and 1986 and limited reforestation from 1986 to 2000 have resulted in a net loss of 0.6 ± 0.1 Tg C. The distribution of carbon densities within the indigenous forest and variation between plantation types suggests that there are management practices that could increase Kakamega's carbon stock back to speculated 1975 levels if not higher. Even given current low carbon prices, a 0.6 Tg C increase in carbon stock could represent a \$3 million value, a figure that dwarfs the operational budgets of the forest's management bodies and could begin to address the income deficit in the region.

1. Introduction

Scientific concerns about the issue of anthropogenically driven global warming and global deforestation trends have driven efforts to better quantify the role of forests, and tropical forests in particular, in the global carbon cycle (Brown, 1997; Houghton, 1997; Watson et al., 2000). As forests are converted to less carbon rich land cover types, such as agricultural fields or urban areas, much of the carbon stored in forest biomass is released into the atmosphere. An estimated 13 million hectares of tropical forest is lost each year to deforestation (FAO, 1999) emitting between 5.6 and 8.6 Gt of carbon (Houghton et al., 1995). Atmospheric carbon dioxide concentrations are increasing, a trend believed to impact the earth's climate, and it is thought that land-use change is responsible for 20-30% of the net increase over the last 20 years (Houghton, 1997). However, the quantification of carbon storage in tropical forests is far from complete. While many studies have aimed to establish carbon storage densities in Neotropical rainforests, estimates still vary by a factor of two (Houghton, 2001). Furthermore, there have been relatively few in depth carbon analyses of Sub-Saharan African forests, which may account for one fifth of global net primary production, (Cao et al., 2001). Quantification of carbon storage in African forests is primarily based on extrapolation from only a few forest surveys and inventory data from the United Nations Food and Agricultural Organization (Brown and Gaston, 1995; Cao et al. 2001). Accurate estimation of carbon storage in tropical forests is challenging, but further refinement of current estimates is crucial to understanding how land-cover change alters the global carbon cycle and how maintaining or enhancing forest cover could be used to mitigate predicted climate change.

International efforts to limit net carbon emissions have resulted in the emergence of a global market for carbon credits earned through activities that offset or reduce emissions. Indeed, over 100 countries have ratified the Kyoto Protocol of the UN Framework Convention on Climate Change, which permits developed nations to obtain carbon reduction credits through investment in emissions reduction or offset projects in developing nations, a system known as the Clean Development Mechanism (CDM). Afforestation, reforestation, and deforestation prevention have been recognized as possible means of offsetting anthropogenic carbon emissions and, as a result, national utilities, private companies, and international consortiums have begun to invest in forestry based carbon offset projects with over 150 bilateral projects having been developed by

2000 (Bass et al., 2000). However, while carbon trading can be a means of supplying developing nations with financial assistance and financial incentive to maintain forests, there is concern that it could shift aid away from Africa in favor of the well studied forests of the Neotropics (Goetze, 1999) and move the focus of forestry towards plantations rather than indigenous forest protection (World Rainforest Movement, 2000).

Model-based assessments of carbon storage in Africa's forests suggest great potential to increase carbon stocks in the region as much of the area that could support carbon rich tropical forests is currently degraded and deforested land (Brown and Gaston, 1995; Zang and Justice, 2001). Brown and Gaston (1995) suggest that Kenya, amongst other African nations, could almost double their aboveground biomass. However, while general models can identify lands that are 'technically suitable' for carbon sequestration, there is little information indicating which areas are 'actually available' for such efforts (Iverson et al. 1993). Detailed local assessments of socioeconomic, political, and cultural factors may be needed to ensure potential carbon storage increases can be achieved in a sustainable manner. Two carbon offset projects in technically suitable areas of Uganda have shown different degrees of success. One project, which established plantations on marginal agricultural lands, resulted in the eviction of 8,000 local inhabitants and the resulting carbon storage has been questioned (Eraker, 2000 a; Eraker, 2000 b; World Rainforest Movement, 2000). A second project, focused on restoring degraded areas in a national forest, has had better results, storing 7.2 Tg C while employing local residents (Watson et al., 2000; World Resources Institute, 2002).

Although there are no forest carbon offset projects operating in Kenya, the deforestation of 93,000 ha of the nation's closed forest in the past decade (FAO, 2001) indicates the potential for forest protection and reforestation projects. The Kakamega National Forest provides a promising and important site for initiating such projects. Believed to be the easternmost relic of the Guineo-Congolian rainforest belt that once spanned the breadth of Africa (Kendall, 1969; Kokwaro, 1988; Wass, 1995), Kakamega is Kenya's only remaining rainforest fragment that is larger than a few hundred hectares. However, rainfall patterns, edaphic conditions, pollen records, and historical accounts indicate that much of western Kenya was once forested and could still sustain closed canopy forest (Kendall, 1969; Kokwaro, 1988; Lovett & Wasser, 1993). The forest is now set in a landscape dominated by small scale agriculture and high population densities of 10 people/ha (Kendall, 1969; Kokwaro, 1988; Wass, 1995; KIFCON,

1993). Regional trends of forest loss have continued even within the national forest boundaries, more than 50% of Kakamega's indigenous forest cover was cleared in a span of 30 years (Wass, 1995; Rogo, 2003), but despite its reduced size, the remaining 14,000 ha of indigenous forest retains a high level of biodiversity and provides resources, ecosystem services, and areas of cultural significance to the region's population. With 350 endemic plant species, 330 bird species, and 6 primate species, it was identified by the IUCN/WWF as a 'biodiversity hotspot' and priority area for conservation in Kenya (Wass 1995). The forest contains the watersheds of the Yala and Isiukhu rivers that provide water to the district and is thought to influence local rainfall patterns (Kokwaro, 1988). Kakamega provides wood to the surrounding population in which 99% of households rely exclusively on firewood or charcoal for cooking (Nambiro, 2000), serves as a grazing and watering area for the 92% of households that own cattle (Sharp, 1993), and is a source of sundry medicinal plants used by local populations (Kokawaro, 1988; Emerton, 1994; Wass, 1995).

While forestry based carbon offset projects cannot sequester carbon at a rate that would counter-act current fossil fuel emissions, they can be effective in mitigating global carbon emissions from land use change and wood consumption if they collectively cover large areas. However, every individual project is implemented on a local scale and local factors inevitably determine its success or failure. Sustainable offset projects depend not only the biophysical potential of an area to sequester more carbon, but also on the project's ability to account for the needs of the area's inhabitants and other stakeholders. This study aims to assess carbon storage in the Kakamega National Forest in order to provide a preliminary assessment of the biophysical potential for further carbon sequestration and suggest some possible management options to achieve this in light of the region's sociopolitical and economic conditions.

2. Methods

2.1 Site description and land use history

The Kakamega National Forest (0° 10'N - 0° 21'N, 34°58'E) of Kenya's Western Province is a 23,700 ha area located on the edge of the Lake Victoria basin. The area is 1520-1680 m above sea level with an annual rainfall of 2,000 mm and a mean daily maximum

temperature of 26°C and mean daily minimum of 11°C . The region's soils are predominantly volcanic clays and clay loams, the majority of which have been classified as ferrallo-chromic acrisols with a few regions on forest edges classified as humic cabrisols and acrisols (Rogo et al., 2003). The official boundaries of Kakamega National Forest, drawn in 1933, encapsulate an area of 23,777 ha, but currently 32 % of this area is agricultural or plantation land and only 60% (14,000 ha) contains closed indigenous forest. The remaining indigenous forest has a 30 m tree canopy dominated by evergreen hardwood species, the most common of which are *Funtumia africana*, *Ficus spp*, *Croton spp*, and *Celtis spp*.

Government management of the Kakamega area was initiated in the 1920s with its designation as a 'County Council Forest' which was accompanied by the eviction of local forest residents. Soon thereafter roads and sawmills were established in the forest. The sawmills extracted the largest trees in their vicinity and converted clear felled areas to timber plantations of valuable indigenous hardwoods (KIFCON, 1994). In 1933, Kakamega became a national forest and its indigenous forest and plantations came under Forest Department (FD) management. By the 1960s plantations of fast growing, non-indigenous softwood species, such as *Pinus spp* and *Cupressus lusitanica*, were introduced to address growing timber and fuelwood demand. In 1986, the felling of indigenous trees was outlawed and all subsequent timber plantations were planted with exotic species e.g. *Pinus spp*, *Cupressus lusitanica*, and *Eucalyptus saligna*, (Kakamega Forest Dept., 2003).

In the 1940s, the FD initiated the "shamba system" (*shamba* is a Kiswahili word meaning small farm) in which local residents were permitted to plant and harvest food crops in Kakamega's plantations while simultaneously intercropping and maintaining timber seedlings. Once the trees became too large, the land was relinquished to plantation. Government concerns over rapid indigenous forest loss, due to clearances for plantations and to forest use by those that moved into the forest to be near their crops, resulted in a freeze on new plantation establishment in the 1970s and a complete ban on the shamba system in 1985. By 1988 all forest residents had been evicted. Without free labor provided by shamba system farmers, the majority of local sawmills went out of business, and without the supplementary farm land in the forest, many households entered food deficit (Sharp, 1993). By 1997, 20% of forest adjacent dwellers (within 10 km of the forest) were landless and households' average annual expenditures exceeded annual incomes from agricultural produce and labor remittances. In response a strictly non-residential

shamba system was re-introduced and, despite the 2000 presidential decree banning logging in Kenya's national forests, a few large logging companies have been permitted to continue operations in the forest (Sharp, 1993).

The indigenous forest area is now under multiple management strategies enforced by different institutions. The FD manages 20,000 ha of which 11,000 ha is indigenous forest. Some extractive forest uses such as cattle grazing and the collection of dead fuelwood, medicinal plants, and thatching grass have always been permitted in much of the forest, but logging and charcoal burning are illegal. There are three zones in which all extractive uses are forbidden: two FD Nature Reserves (700 ha total) established in 1967 and the Kakamega National Reserve (4,000 ha) established in 1985 and managed by the Kenya Wildlife Service (KWS). In comparison to FD areas, the national reserve is more heavily patrolled, has more severe penalties for offenses, and, starting in 2003, requires a fee for entry. Unlike the FD, which relies on national budget allocation to fund its operations, KWS is a quasi-governmental body that is permitted to retain all the revenues it produces. As a result, the FD's Kakamega station manages 20,000 ha on an annual budget that is approximately 10% of its annual earnings and 15% of the KWS station's annual budget used to manage the 4,000 ha reserve.

Households adjacent (within 10 km) to FD managed areas continue to rely heavily on extracted forest resources, both legally and illegally (Emerton, 1994; Sharp, 1993; Nambiro, 2000). Surveys in 1993 revealed that, while households residing adjacent to the KWS reserve received almost no income from the forest, in areas adjacent to the FD forest, approximately 60% of average household income was directly tied to forest use (Emerton 1994, Sharp 1993). In response to continued forest degradation, many non-governmental organizations and grass roots organizations initiated projects in and around the forest in the 1990s. Projects were primarily geared towards decreasing reliance on extractive uses of the forest through education, efforts to foster cooperative management, microlending, agroforestry, tourism centers, and other alternate income projects (KIFCON 1994, ICIPE 2001, KEEP 2003).

2.2 Sampling design

Carbon density was estimated based on data taken in ninety-five 20x20m sample plots for six carbon storage pools: live tree aboveground biomass, tree belowground biomass, coarse

deadwood (≥ 10 cm diameter), litter, herbaceous vegetation, and soil (Brown, 1997; MacDicken 1997). All samples were taken between 11 June and 8 August, 2003.

Plots were stratified by land cover, age, and managing organization. Plot stratification was based on Kakamega land cover maps for 1975, 1986, and 2000 as created by Kenya Department of Remote Sensing and Resource Surveys (DRSRS) from interpretation of Landsat TM satellite images and aerial photographs (Rogo et al., 2003). Sampling was performed in the three tree cover types identified on the maps: indigenous forest, hardwood plantation, or softwood plantation. Within each tree cover type, sample plots were further stratified by relative age: 'young' plots being in forest or plantations first appearing between 1986 and 2000 (≤ 14 years old in 2000) and 'old' plots being forest or plantations present since 1986 or earlier (> 14 years old in 2000). To identify areas of these different age classes, the 1986 and 2000 land cover maps were overlain using ArcView GIS © (Environmental Systems Research Institute, Inc., USA) software. Under this classification, 'young' indigenous forest represents forest regenerating on land formerly of a different use, while 'old' forest represents land that has been forested for a longer period, but contains a mosaic of forest ages due to local disturbances. Plantation groupings also contained a range of ages and registers indicate that some of the 'old' hardwood plantations may be as old as 50 years while others might be half as old (Kakamega Forest Department, 2003). The indigenous forest plots were also classified as being in either Forest Department (FD) or Kenya Wildlife Service (KWS) management areas.

The number of plots sampled in each class was roughly proportional to the relative area covered by each class and the predicted spatial heterogeneity of carbon density within each class. Heterogeneity was assumed to be greater in indigenous forest and mixed species plantations than in monoculture plantations. Within the indigenous forest, access paths crossing the forest were used as sampling transects and plots were located using a random number generator to dictate the perpendicular distance from a path. Based on examination of the Kakamega Plantation Registry (Kakamega Forest Department, 2003), plantation plots were randomly located within plantation blocks containing species representative of the plantings in each of the common types: indigenous hardwoods (mixed species plantations or monocultures of *Maesopsis eminii*, *Prunus Africana*), exotic hardwoods (*Eucalyptus saligna*, *Bischofia javonica*), and exotic softwoods (*Pinus patula*, *Cupressus lusitanica*). It was not possible to determine the total planted area of each species as this information has not been mapped or reliably recorded.

All plot positions were recorded using a GPS unit and later geo-referenced to the land-cover maps. Plots were generally assigned to a cover class by their geo-referenced location on the 2000 land cover map. Plots for which a ground-based assessment of land cover did not match the map classification were assigned to the cover class seen on the ground only if the plot position appeared to have been misplaced on the map as a result of a GPS error. In addition, plots were classified as being visibly disturbed by extractive use (grazing, firewood collection, logging, and charcoal burning) based on the presence or absence of established paths, clearly cut stumps and branches, or charcoal pits,

2.3 Estimation of carbon density and current carbon storage

2.3.1 Vegetative biomass

To quantify aboveground biomass, tree and liana diameters were recorded at 1.3 m from the ground (dbh), in ninety-five 20m x 20m plots. In each plot, diameters of all trees with a dbh of >20cm were recorded. All trees with dbh >5 < 20 cm were measured in a 10m x 10m nested subplot. For trees with buttressed roots, diameters were measured at the point at which buttresses merged with the bole of the tree if this point was above 1.3 m and below 3m. However for trees that had larger buttresses, the diameter was taken at 1.3m and adjusted using a proportional correction factor. Diameter correction factors were calculated for a given species from measurements of average buttress protrusion at 1.3 m from what was assumed to be a circular central bole (Appendix A).

The species of each measured tree was recorded and an importance value of each species observed in indigenous forest plots was calculated as described by Brower et al. (1998):

$$Importance\ value_x = \frac{relative\ density_x + relative\ frequency_x + relative\ coverage_x}{3}$$

where:

relative density_x = number of trees of species x / total number of trees observed

relative frequency_x = frequency of species x amongst sample plots / sum of frequencies of all species observed

relative coverage_x = percent of sampled area covered by species x basal area / sum of coverages of all species observed

The biomass of each tree was calculated based on diameter using published allometric equations (Appendix B). For exotic plantation species, *Eucalyptus saligna*, *Cupressus lusitanica*, and *Pinus patula*, species specific equations were applied (Specht & West, 1998; Monteith, 1979; Brown, 1997). For indigenous species, a generalized tropical moist forest equation was used (Brown, 1997). Calculated aboveground biomass of indigenous trees with low published wood densities: *Funtumia africana*, *Ficus spp*, *Maesopsis eminii*, *Macaranga kilimansharica*, and *Trema orientalis* (Brown, 1997) was adjusted using the ratio of the species wood density to the average density of trees used to derive the generalized equation (Chave et al., 2003). Liana aboveground biomass was calculated using a multi-species liana equation (Putz, 1983). Belowground biomass was calculated as a proportion of aboveground biomass using a root-shoot biomass ratio of 0.24 derived for tropical trees by Cairns et al. (1997).

The biomass of coarse deadwood was estimated in each plot by measuring diameters of all downed trees with diameter ≥ 10 cm along two perpendicular 20m transects (northern and eastern edges of each 20x20 m plot). Each measured tree was given a decomposition ranking: rotten, intermediate, or sound as described by Harmon & Sexton (1996). The biomass density of this deadwood was calculated using Harmon & Sexton's (1996) method using the tropical deadwood densities for the three decomposition classes reported by Clark et. al (2002). Standing dead trees were measured with live standing trees, but they were similarly given a decomposition ranking and density by which to scale their biomass.

In forty-seven plots, selected in a stratified random design from the 95 tree inventory plots, clip plots were used to measure understory vegetation and litter (MacDicken, 1997). At each corner of the 20m x 20m inventory plot a 0.5 x 0.5 m subplot was established and all understory vegetation in the four subplots was cut and placed in a weigh bag. The wet weight was recorded, the sample was well mixed, and a 200g sub-sample was taken, air dried for at least 3 weeks, and reweighed. The wet to dry weight conversion of the subsample was used to estimate total dry weight for herbaceous vegetation. This same procedure was followed for litter which was collected in each clip plot after herbaceous vegetation was removed.

2.3.2 Soil carbon

Soils were sampled in the same subplots as herbaceous vegetation and litter. After the vegetation and litter was removed, a 60 cm soil pit was dug and three subsamples collected at 20

cm increments by taking a vertical slice of the pit wall with a knife. Soil samples were air-dried, passed through a 2mm sieve, and pulverized. Sample carbon concentrations were predicted using the spectral library approach described by Shepherd and Walsh (2002). All samples were analysed by diffuse reflectance spectroscopy, using a FieldSpec FR spectroradiometer (Analytical Spectral Devices Inc., Boulder, Colorado) at wavelengths from 0.35 to 2.5 μm with a spectral sampling interval of 1 nm using the optical setup described in Shepherd et al. (2003). Carbon was measured on a random selection of 61% of the samples (86 samples) by the modified Dumas method, in which 10 mg aliquots were combusted in an automated nitrogen-carbon analyzer (NC 2100). Measured concentrations for this subset were calibrated to their reflectance spectra using partial least squares regression with Unscrambler 7.5 © software (CAMO Inc., Corvallis, OR., USA). The regression models were used to predict C concentrations for all samples. The average carbon concentration at each depth was found for each sampled strata and multiplied by the bulk density of Kakamega forest soils ($0.637 \text{ g/cm}^3 \pm 0.033 \text{ g/cm}^3$) reported by Awiti (2003) to estimate soil carbon density (Mg C/ ha).

2.3.3 Aggregation and extrapolation

Average carbon density estimates for the sampled land cover classes were calculated by aggregating contributions from all measured carbon pools. It was assumed that 50% of vegetative biomass was carbon (MacDicken 1997) allowing carbon densities (Mg C /ha) to be calculated from biomass densities found in each plot. The mean plot carbon density was found for a land cover class in each carbon pool and the sum of the pool means was taken to be the average carbon density for the class. Calculated cover class averages were applied to the entire area of that land-cover class in the 2000 cover map to calculate total carbon storage in the Kakamega Forest.

The heterogeneous nature of tropical forests creates the distinct possibility that randomly distributed plots may not capture a representative sample of the carbon density range in the forest (Chave et al 2003, Houghton et al. 2001, Keller et al. 2001). Therefore the distribution of plot carbon densities was assessed and an interpolated carbon density surface was created for the indigenous forest area as an alternative method to determine total carbon storage without extrapolating a mean value. To create the interpolated surface, the indigenous forest area was converted to a grid with a cell size of one hectare and the carbon densities of the geo-referenced

sample plots were assigned to the grid cells in which the plots were located. Carbon density values were assigned to the remaining cells based on inverse distance weighting (IDW) of the carbon density values of the five plots nearest to a cell. The IDW function in ArcView GIS © (Environmental Systems Research Institute, Inc., USA) has been similarly used in studies of the Brazilian Amazon (Houghton et al. 2001) and the nearest neighbors (N-kk) approach using the 5 or 10 closest plots has been used for interpolating carbon density from plot data (Reese et al. 2002). The inclusion of the five nearest neighbors in the interpolation was chosen based on an analysis of which number of neighbors most accurately predicted the measured values in cells containing sample plots (Appendix C). Given a surface of carbon density values in Mg C/ha and cell size of 1 ha, the sum of all cell values in the area produced an estimate of the total carbon storage in the natural forest area.

2.3.4 Statistical analyses and uncertainty assessment

One-way ANOVA was used to detect significant differences between carbon density averages amongst land cover classes. Pair-wise comparisons between classes were made using standard student's t-tests except in the case of the tree aboveground biomass carbon densities, which were found to have a positively skewed distribution. Tukey's HSD test was used for pairwise comparisons of tree above-ground biomass.

To calculate uncertainty in average carbon density values, 5,000 iteration Monte Carlo analyses were run for each land cover class with Crystal Ball 5.5 © (Decisioneering, Inc., USA) software using probability distributions of tree diameter and plot size measurements, wood density adjustments, and buttress correction factors. A sensitivity analysis was used to assess the relative influence of these factors on the aggregate mean values. The uncertainty range of the total carbon stock for the forest was calculated by scaling the uncertainty range of each cover class by its aerial contribution to the total forest area.

2.4 Spatial analysis of carbon distribution in indigenous forest

Geo-referenced data of the locations of towns, roads, rivers, park boundaries, and rivers included in the DRSRS land cover maps were used to look for significant trends in carbon storage values with distance from a potential cofactor. Factors, such as accessibility for grazing or logging, probability of being caught by a forest guard while logging, or proximity to surface

water, that may influence species distribution, tree size, tree abundance, or soil quality, could in turn effect carbon density. However, as the plot sampling distribution was based on the assumption that variation within a land cover class was random, as opposed to distributing plots with the aim of assessing changes in carbon storage over a distance gradient, these comparisons are merely exploratory and not meant to be conclusive. The Program R 4.0 was used to assess the existence of any spatial autocorrelation in carbon density data without reference to a particular cofactor.

2.5 Assessment of land cover change (1975-2000) effects on carbon storage estimates

ArcView GIS © (Environmental Systems Research Institute, Inc., USA) was used to overlay the Kakamega Forest land cover maps from 1975, 1986, and 2000 to quantify the changes in land cover over time and examine their spatial distribution. To estimate change in Kakamega's carbon stocks resulting from land cover changes in this time period, it was necessary to assume that the data collected in this study is similar to what would have been found in the same land cover classes in 1975 and 1986. Land cover classes in 1975 and 1986 maps could not be stratified into young and old as was done for the 2000 map due to a lack of spatially explicit information on forest cover before 1975 and due to unequal time periods between map pairs (1975-1986, 1986-2000). Therefore, an area-weighted average was calculated for each tree cover type (indigenous forest, hardwood plantation, and softwood plantation) based on the distribution of young and old forest area in 2000. These weighted averages were multiplied by the areas of each class found in each of the land cover maps to approximate total carbon stocks under the assumption that the proportion of young and old forest was the same in 1975 and 1986 as in 2000.

3. Results

3.1 Carbon densities in land cover classes

The area-weighted mean carbon density for indigenous forest was 330 ± 65 Mg C/ha ($\pm 19\%$ at 95% confidence interval of the mean), which was greater than that of hardwood

plantations, 280 ± 77 Mg C/ha, and significantly greater than that of softwood plantations, 250 ± 78 Mg C/ha (Table 1). However, when comparing age stratified classes, old hardwood plantation mean carbon density (370 ± 90 Mg C/ha) was similar to old indigenous forest (360 ± 63 Mg C/ha) and young hardwood plantations had greater mean carbon density (240 ± 71 Mg C/ha) than indigenous forest (170 ± 78 Mg C/ha). In neither case were means significantly different. However, because 70% of the area covered by hardwood plantation in 2000 was ‘young’ (lower mean carbon density), the area-weighted average was lower than that of the indigenous forest class, which was 89% ‘old’. Stratifying indigenous forest plots into KWS vs. FD managed areas did not produce statistically significant values in either old (KWS: 370 ± 94 Mg C/ha, FD: 340 ± 80 Mg C/ha) or young (KWS: 160 ± 86 Mg C/ha, FD: 160 ± 42 Mg C/ha) forest plots.

Table 1. Mean carbon densities for land cover classes in the Kakamega Forest for the year 2000

Tree cover class	Age class	Number of plots	Mean carbon density (Mg C/ha \pm 95% CI)	Area in 2000 (ha)	Percent of total class area	Area weighted carbon density (Mg C/ha \pm 95% CI)	Total carbon in cover class (Tg C \pm 95% CI)
indigenous forest	old*	46	360 ± 63	12391	89%	330 ± 65	4.7 ± 0.90
	young	16	170 ± 78	1576	11%		
hardwood plantation	old*	13	370 ± 90	923	29%	280 ± 77	0.87 ± 0.24
	young	10	240 ± 71	2208	71%		
softwood plantation [#]	old	5	290 ± 82	279	44%	250 ± 78	0.15 ± 0.05
	young	5	210 ± 75	353	56%		
TOTAL							5.7 ± 1.2

* significantly greater mean carbon storage than young plots of the same tree cover type, $\alpha = 0.05$

[#] significantly lower mean carbon density than both old indigenous forest and old hardwood plantation, $\alpha = 0.05$

Tree biomass accounted for 60-70% of ecosystem carbon in indigenous forest plots (Table 2). The tree species distribution in young, regenerating forest was found to be different than that observed in the mature forest. (Table 3). This distribution confirms previously observed successional patterns (Kokwaro, 1988; Earlham University, 1999)

Table 2. Distribution of carbon in carbon pools among forest types.

Carbon pool	Mean carbon density (Mg C/ha ± 95% CI) in carbon pool and % of total mean cover class carbon density					
	indigenous forest		hardwood plantation		softwood plantation	
	old	young	old	young	old	young
Above ground tree biomass	200± 36 55%	81± 32 48%	200± 49 54%	111 ± 44 47%	150 ± 50 52%	72 ± 29 34%
Below ground tree biomass	49± 9 14%	20± 8 12%	51± 12 14%	28± 11 12%	38± 12 13%	18± 7 9%
Total tree biomass	250± 45 69%	100± 40 59%	250± 62 68%	140± 54 58%	190± 62 65%	90± 36 43%
Deadwood biomass	1.2± 0.4 0.30%	0.1± 0.1 0.10%	0.7± 0.4 0.20%	0.4± 0.5 0.20%	0.7± 1.1 0.20%	0.5± 0.7 0.30%
Soil carbon	100± 17 29%	63± 36 37%	110± 37 30%	93± 24 39%	94± 15 32%	120± 41 56%
Herbaceous biomass	0.8± 0.4 0.20%	0.3± 0.1 0.20%	0.9± 0.4 0.20%	0.8± 0.6 0.30%	0.3± 0.1 0.10%	0.3± 0.1 0.20%
Litter biomass	5.4± 0.9 1.50%	5± 1.4 3.00%	6.3± 2.0 1.70%	4.2± 1.3 1.80%	6.2± 2.1 2.10%	2.7± 1.7 1.30%
Total mean carbon density	360 ± 63	170 ± 78	370 ± 90	240 ± 71	290 ± 82	210 ± 75

Table 3. Top ten species ranked by importance value for indigenous forest plots

Rank	Old indigenous forest		Young regenerating forest	
	Species	Importance Value	Species	Importance Value
1	<i>Funtumia africana</i> (most common canopy species ⁺)	12.5%	<i>Bridellia micrantha</i>	22.3%
2	lianas	7.5%	<i>Harungana madagascariensis</i> (listed primary colonizer*)	12.8%
3	<i>Ficus exasperata</i>	6.0%	<i>Psidium quajava</i> (exotic hardwood)	10.5%
4	<i>Croton megalocarpus</i> (listed canopy species*) <i>Teclea nobilis</i>	4.9%	<i>Vernonia amygdalina</i> (shrub)	4.8%
5	<i>Bequaertiodendron oblanceolatum</i> , <i>Trilepsium madagascariensis</i>	3.9%	<i>Solanum mauritania</i> (shrub)	2.7%
6	<i>Celtis durandii</i>	3.8%	<i>Antiaris toxicaria</i> , <i>Maesa lanceolata</i> (shrub) <i>Cupressus arizonica</i> (exotic softwood)	2.5%
7	<i>Rinorea bachaepetala</i>	3.6%	<i>Bersama abyssinica</i> (listed primary colonizer*)	2.4%
8	<i>Celtis mildbraedii</i>	3.2%	<i>Albizia gummifera</i> (listed secondary colonizer*)	2.3%
9	<i>Ficus sur</i>	2.7%	<i>Acanthus eminens</i> (listed primary colonizer*)	2.1%
10	<i>Antiaris toxicaria</i> (listed canopy species*)	2.5%	<i>Prunus africana</i>	1.9%

⁺ Kokwaro, 1988 * Earlham University, 1999

Soils contained a substantial amount of carbon in the indigenous forest, making up 37% of the average carbon density in young plots and 29% in old (Table 2). Mean soil carbon densities in all cover classes were close to 100 Mg C/ha and did not vary significantly between classes with the exception of young indigenous forest plots, which had a low soil carbon density of 63 ± 36 Mg C/ha, significantly different from other strata ($p < 0.1$). This may be the result of the land uses predating the regenerating forest, which were pasture or grassland for 70% of regenerating plots. A quarter of the soil samples from young indigenous forest came from areas with a different soil classification, cambisol/acrisol, than the rest of the sampled areas classified as ferrallo-chromic acrisols (based on Rogo et al. 2003 soil map). This younger soil type may have lower organic matter content.

Hardwood plantations had a mean carbon density similar to that of indigenous forest and similar distributions of carbon within the largest ecosystem compartments: aboveground biomass (68% in young, 58% in old) and soil (37% in young, 30% in old). Old softwood plantations, while having lower overall carbon density than the other tree cover types, also had relatively similar carbon partitioning (65% in trees, 32% in soil) to other classes. In young softwood plantations, a class with both smaller trees and lower wood densities, a greater proportion of the stored carbon was found in soils (56%) than in tree biomass (43%). As expected, deadwood, litter biomass, and herbaceous biomass contributed relatively little to the total carbon pool, cumulatively contributing under 3% of the total carbon density in most forest types.

Table 4. Range of tree biomass carbon density values amongst plots in each land cover class

Tree cover class	Age class	Plot tree carbon density estimate (Mg C/ha \pm 95% CI) and coefficient of variation (CV)				Class range (Mg C/ha)
		Lowest value	CV	Highest value	CV	
indigenous forest	old	49.8 ± 25.4	0.13	657 ± 230	0.11	607
	young	14.2 ± 2.1	0.04	209 ± 23.2	0.03	195
hardwood plantation	old	64.9 ± 34.3	0.13	405 ± 219	0.13	340
	young	14.2 ± 7.9	0.14	232 ± 125	0.13	218
softwood plantation	old	88.9 ± 49.1	0.13	200 ± 88.0	0.11	111
	young	29.8 ± 14.8	0.09	85.9 ± 31.0	0.12	56

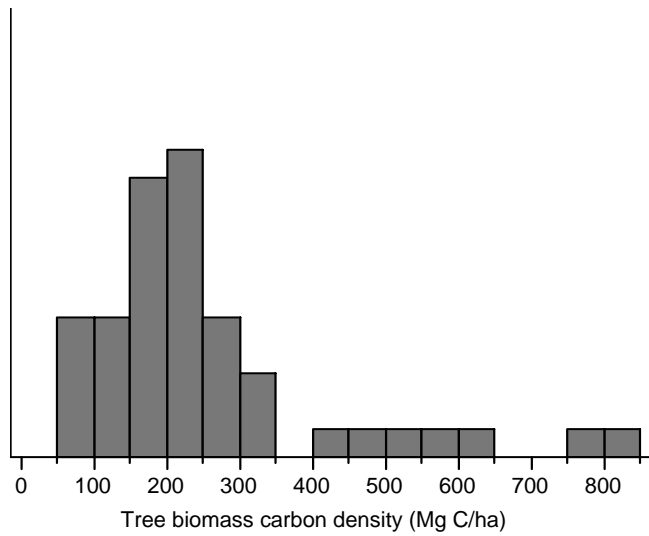
There was a large range of carbon densities in each cover class, but the greatest variation was observed in old indigenous forest: plot aboveground biomass carbon densities in old forest

Figure 1: Distribution of carbon densities among sample plots in indigenous forest in which tree biomass (46 old plots, 16 young plots) and soil carbon (17 old, 9 young) were measured. **a)** Carbon density distribution for tree biomass in old indigenous forest plots **b)** Carbon density distribution for tree biomass in young indigenous forest plots **c)** Carbon density distribution for soils in old indigenous forest plots **d)** Carbon density distribution for soils in young indigenous forest plots

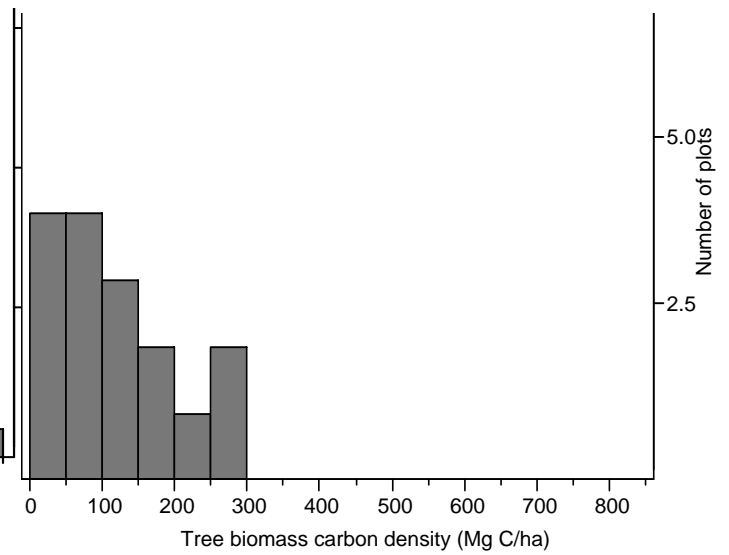
Old indigenous forest

Young indigenous forest

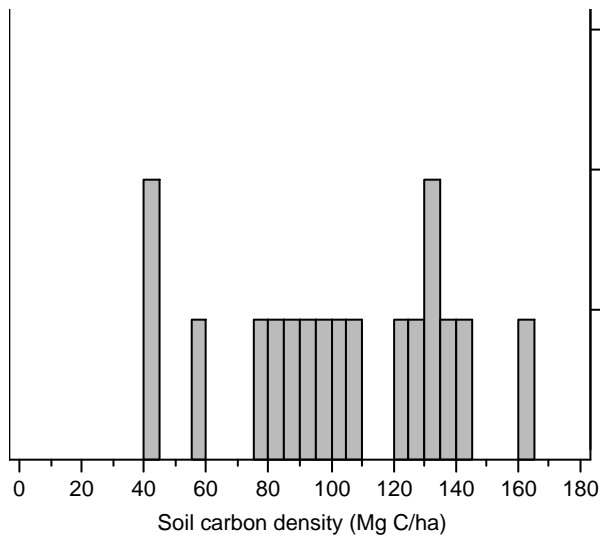
a)



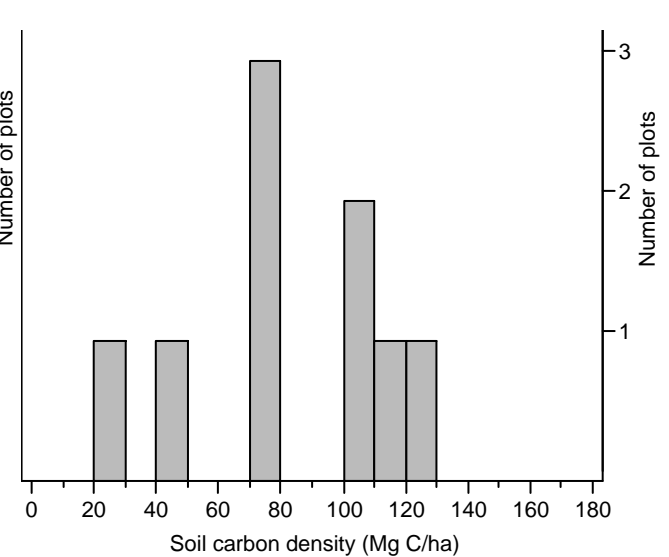
b)



c)



d)



ranged by 600 Mg C/ha, almost twice the range seen in other classes (Table 4). Amongst plots in which all six carbon pools were sampled, total carbon storage values ranged by 840 Mg C/ha in old and 270 Mg C/ha in young indigenous forest, by 290 Mg C/ha in old and 220 Mg C/ha in young hardwood plantation, and by 150 Mg C/ha in old and 170 Mg C/ha in young softwood plantation. The distribution of tree biomass carbon densities among both old and young indigenous forest plots was non-normal and positively skewed (Figure 1). Soil carbon densities also showed a wide variation in old indigenous forest plots, with a range of 120 Mg C/ha, but with a less skewed distribution (Figure 1). Indigenous forest plots with greater tree carbon storage tended to show a linear positive correlation with soil carbon ($p < 0.05$, $r^2 = 0.32$).

Plantations sampled within hardwood and softwood classes showed a range of carbon density values depending on both age and species. With the exception of *Eucalyptus saligna*, hardwood species take longer to reach harvestable maturity than softwood (Table 5). Mature indigenous hardwood and *Bischofia javonica*, (exotic tropical hardwood) plantations had carbon densities between 360 Mg C/ha and 400 Mg C/ha, values higher than the mean found in indigenous forest plots. Mature plantations of the faster growing, low wood density species had carbon densities that were one half to two thirds the values found for the indigenous hardwoods: *Eucalyptus saligna* (190 Mg C/ha), *Cupressus lusitanica* (220 Mg C/ha), and *Pinus patula* (240 Mg C/ha). However, these low carbon density plantations were also roughly half the age of the high density hardwoods.

Table 5. Carbon densities of plantation types common to Kakamega Forest

Plantation type	Species origin	Species	Harvestable age (years)	Carbon density at maturity (MgC/ha)
Hardwood	Indigenous	Mixed Indigenous	40	360
		<i>Maesopsis eminii</i>	40	390
		<i>Prunus africana</i>	40	400
	Exotic	<i>Bischofia javonica</i>	30	360
		<i>Eucalyptus saligna</i>	10	190
Softwood	Exotic	<i>Cupressus lusitanica</i>	20-30	220
		<i>Pinus patula</i>	20-30	240

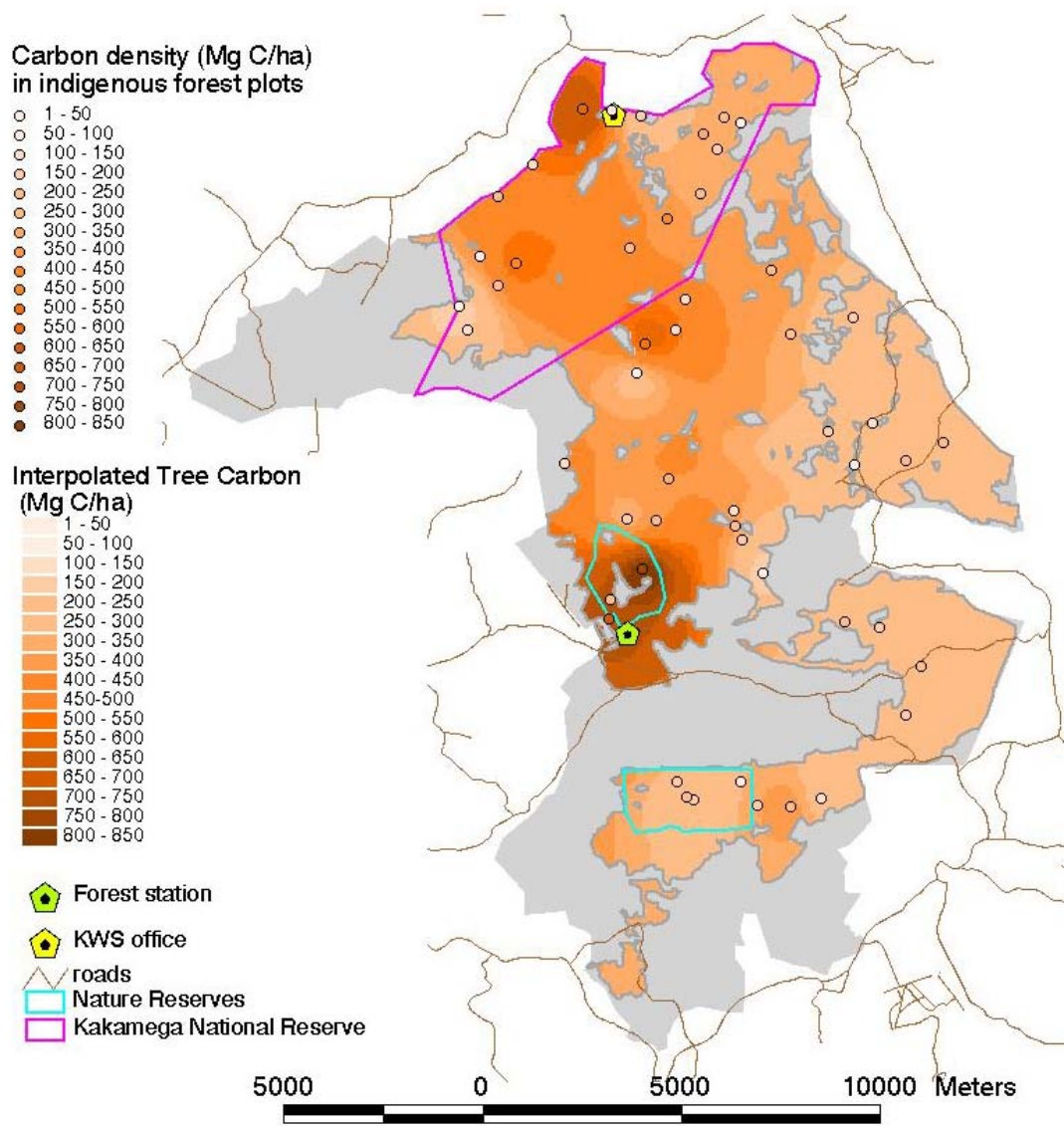


Figure 2. Interpolated carbon density surface. The natural forest area was transformed into a grid with 1 hectare cells. Interpolated carbon density values were assigned to each grid cell based on plot data from 62 indigenous forest plots. Grid cells were assigned carbon density values based on an inverse distance weighting (IDW) of values of the five closest plots.

3.2 Current carbon storage

Extrapolating the mean carbon density of each cover class to the entire area of that cover class in the year 2000 yielded an approximate total carbon storage value of 5.7 ± 1.2 Tg C for the Kakamega Forest (Table 1), the majority of which was in the indigenous forest (4.7 ± 0.9 Tg C).

To avoid extrapolating the mean of a non-normal distribution over the entire indigenous forest area, the total carbon stored in indigenous forest tree biomass was also calculated using IDW interpolation of tree biomass carbon density (Figure 2). This procedure yielded a value of 3.2 Tg C stored in indigenous forest trees. When added to the contributions from the mean carbon densities in soils, litter, deadwood, and herbaceous vegetation (1.5 Tg C in sum), the total carbon storage in indigenous forest was 4.7 Tg C, the same value found using the mean plot carbon density approach.

3.3 Error and uncertainty analysis

Uncertainty in dbh and plot area measurements introduced relatively little uncertainty in the mean carbon density estimates compared to other sources of error. Buttress and wood density adjustments had fairly large influences on indigenous forest and hardwood plantation aboveground biomass values, without changing softwood plantation estimates. This had the effect of bringing the carbon density means of the indigenous forest and hardwood plantations closer to those of the softwood plantations; however, they remained discernibly larger than the softwood means.

In indigenous forest 30% of old plots and 37% of young plots contained buttressed trees while they were only found in 17% of hardwood plantation plots. Using the proportional adjustment factors to calculate the diameters of these buttressed trees decreased mean aboveground biomass carbon values by about 15% (14-17%) from the unadjusted value for both the young and old plots in forest and hardwood plantation. This assumption did not change the relative differences among class means by more than 15 Mg C/ha, which is small in comparison to the size of the 95% confidence intervals of the means themselves. In fact, adjusting for buttresses decreased variation among plot carbon densities within classes.

Fifty percent of both indigenous forest plots and hardwood plantation plots contained at least one *Funtumia africana*, *Ficus spp*, *Maesopsis eminii*, *Macaranga kilimansharica*, or *Trema orientalis* tree . Adjusting for the relatively low wood densities of these species decreased mean aboveground biomass carbon densities by 9-11% from unadjusted values in old plots and 6-7% in young plots of the effected classes. However, this did not change the ranking of the land cover class carbon density means or the significant differences between means. The adjustment also decreased standard deviations within the effected classes.

The large variation among plots within each cover class accounted for most of the uncertainty in mean carbon density values, dwarfing all other sources of error. An aggregate estimate of uncertainty in the carbon density values for individual plots resulted in coefficients of variation (CV) ≤ 0.13 for plots in all land cover classes, attributable to estimated measurement errors and uncertainty in biomass adjustment factor values (Table 4). However, when potential measurement errors and adjustment uncertainties are ignored, the CVs of the overall carbon density means for all land cover classes remained high (0.62 for old indigenous forest, 0.53 for young indigenous forest, 0.43 for old hardwood plantations, 0.69 for young hardwood plantation, 0.37 for old softwood plantation, and 0.65 for young softwood plantation) as a result of within class variation.

3.4 Patterns in carbon density distribution

While there was no significant spatial autocorrelation in the data, some patterns in carbon storage were apparent in the indigenous forest. It was found that visibly disturbed plots had lower carbon densities on average than those in which human disturbances were not observed (30 Mg C/ha less, $p < 0.05$). Visibly disturbed plots were closer to forest access points on average (agricultural areas, grazing areas, paths, and roads), but there was no statistically significant trend. Straight-line distance from various sources of anthropogenic influence was found to have weak, and for the most part insignificant, power to predict plot carbon densities in indigenous forest in linear regression analyses (Table 6) and nonlinear relationships did not improve fit. Plot carbon density showed a small, but significant increase with distance from towns and roads ($R^2 \approx 0.1$). While no significant linear relationship was established at this sampling intensity, visual analyses of the interpolated carbon density surface (Figure 2) revealed a clustering of high carbon density plots near the KWS and FD forest stations. Average carbon density within 2km of either forest station was 280 Mg C/ha greater than the average for plots located at distances greater than 2 km from a station ($p < 0.05$).

Roughly 80-90% of the differences in carbon density among plots was the result of differences in tree biomass. The number of large ($\text{dbh} \geq 50\text{cm}$) and very large trees ($\text{dbh} \geq 70\text{cm}$) in a plot predicted over 50% of the variation in plot carbon densities in the indigenous forest ($p <$

0.05). Species richness and tree abundance also showed significant covariance with carbon density but explained little of the variation (Table 5).

Table 6: Results of linear regression analyses of possible carbon density covariables in indigenous forest plots

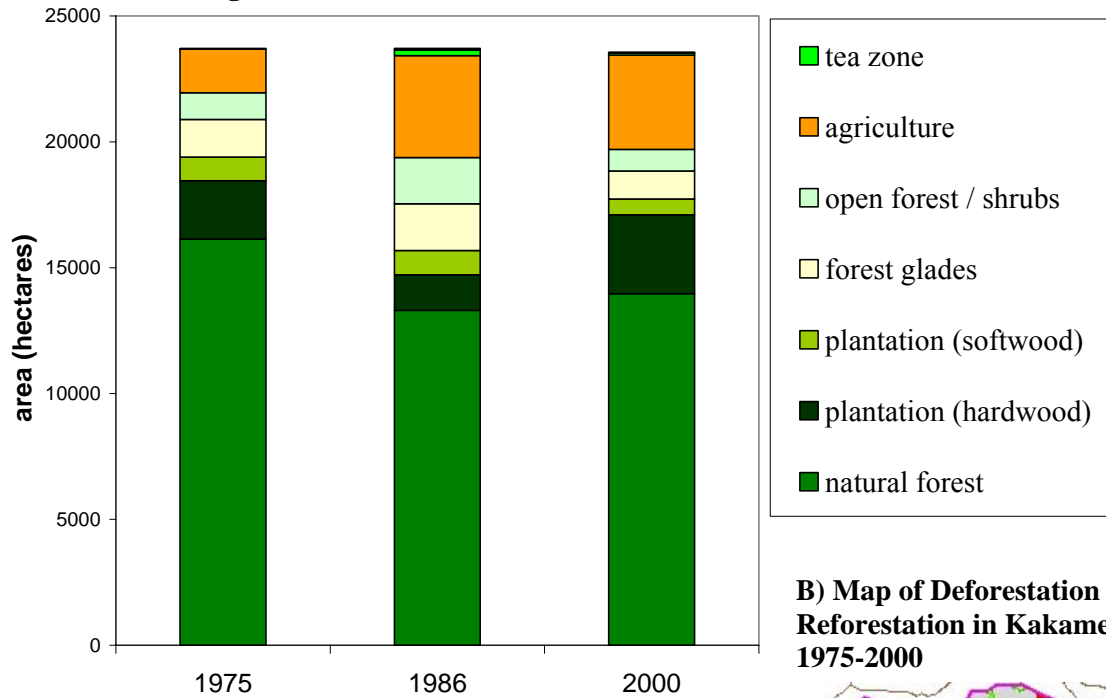
Plot carbon density predictor variables	R²
<i>anthropogenic influences</i>	
distance from forest station	-0.009
distance from town	0.087**
distance from road	0.056*
distance from forest paths	0.015
distance from grazing area	0.000
distance from agriculture	0.010
<i>forest structure</i>	
species richness (number of species in plot adjusted by abundance)	0.067**
tree abundance (stems/ ha)	-0.036*
number of large trees (dbh≥50cm) in plot	0.573**
number of very large trees (dbh≥70cm) in plot	0.550**
(* statistically significant at $\alpha = 0.1$, ** statistically significant at $\alpha = 0.05$)	

3.5 Effects of land cover change since 1975

In 1975, 82% of the Kakamega National Forest's 23,700 ha area had tree cover, of which 68% was indigenous forest. Agricultural lands (7% of the area) were found near the plantation blocks on forest roads and along forest margins. As a result of forest losses between 1975 and 1986 and reforestation between 1986 and 2000, Kakamega experienced a 9% net decline in total tree covered area (forest and plantation) and a 14% (2,200 ha) net decline in natural forest area in the 25 year time period. (Figure 3, Table 7) This may have resulted in the loss of 0.4 - 0.6 Tg C.

Between 1975 and 1986, Kakamega lost 18% (2,830 ha) of its 1975 natural forest cover. Indigenous forest was mostly lost to agricultural use (52% of net loss), but also to the expansion of grasslands and open forest (45% of net loss). While there was an almost 40% decline in hardwood plantation tree cover in this period, agricultural areas seen in former plantations (48% of the loss) would have been under shamba system cultivation if planted before the 1985 ban and hence would contain the next rotation of timber seedlings. Assuming that the age and species compositions of forest and plantations in 1975 and 1986 were similar to those found in 2000, the observed land cover changes would have resulted in a loss of 19% (1.2 Tg C) of Kakamega's carbon stock and indigenous forest losses would account for 80% (0.95 Tg C) of the total loss (Table 7)

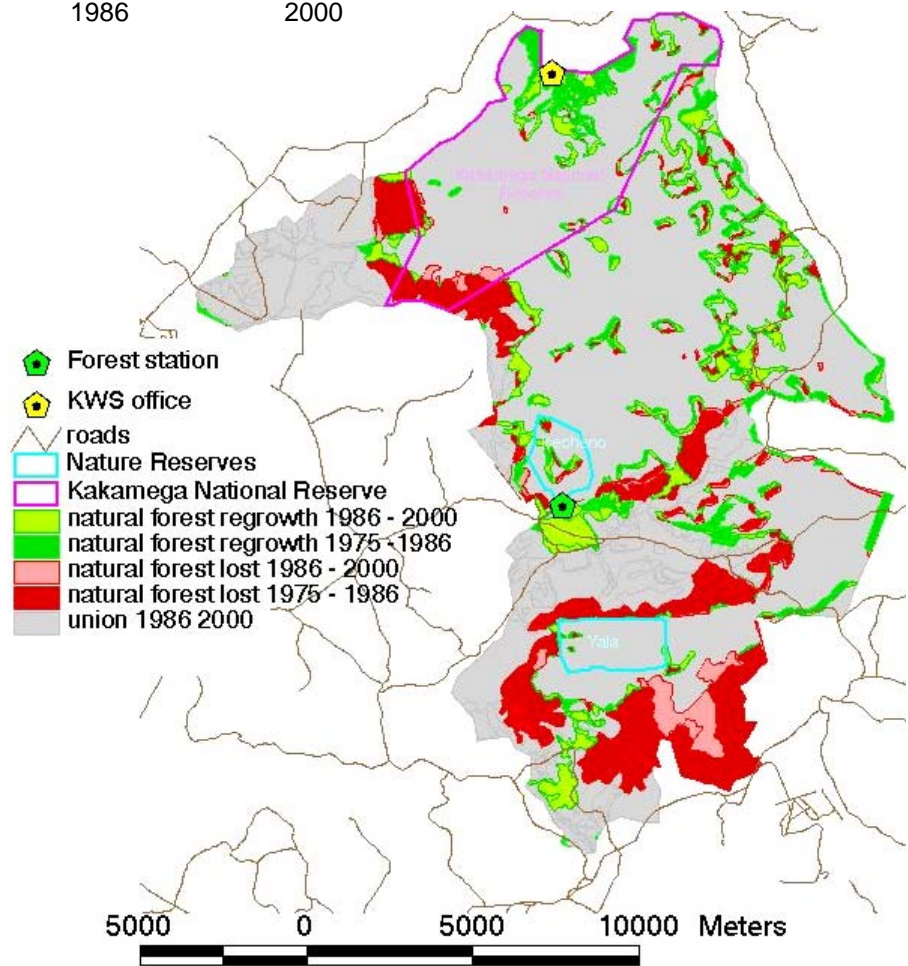
A) Kakamega Forest land cover 1975 to 2000



B) Map of Deforestation and Reforestation in Kakamega 1975-2000

Figure 3: A) The distribution of land cover types in the Kakamega National Forest (1975-2000).

B) Overlaying the GIS maps of land cover illuminates the locations of land cover change. As seen in red, deforestation and agricultural expansion has resulted in the loss of forest cover at the southern and northwestern edges of the forest, mostly between 1975-1986 (darker red). As seen in green, grassland regeneration reforested the areas around the KWS and FD stations from 1986 to 2000 (brighter green).



From 1986 to 2000, there was a 13% net increase in total tree covered area. Indigenous forest cover increased by 700 ha (5% net increase) to cover 86% of its 1975 extent and the area covered by planted hardwoods doubled. Net forest regeneration in grassland and open forest, occurring primarily near forest stations, was responsible for 72% of the indigenous forest increase. Overall grassland and open forest regeneration in this period was similar in the KWS managed National Reserve (46% of grassland areas regenerated) and in the FD managed forest (40% regenerated).. Forest re-growth did occur on abandoned agricultural land, accounting for 13% of the net increase, however of the 1,400 ha of agricultural land that gained tree cover in 1986-2000, 70% was converted to hardwood plantation perhaps due to the re-introduced shamba system. While there was a net loss of softwood plantation in this period, it was replaced by agriculture presumably under the shamba system and will likely return to plantation tree cover with time.

Land cover changes between 1986 and 2000 may have resulted in 0.62 Tg C increase in carbon storage. Under the given assumptions, the regeneration of 700 ha of indigenous forest would result in storage of 0.22 Tg C and the addition of 1,700 ha of hardwood plantation would have stored 0.48 Tg C. The clearance of 335 ha of softwood plantation would have produced a relatively small loss of total carbon storage (0.08 Tg C) due to its low carbon density.

Table 7: Carbon stored in the Kakamega Forest (1975-2000) based on area-weighted carbon density averages for cover types in the year 2000

Tree cover	Mean carbon density (Mg c/ha)	1975		1986		2000	
		Area (ha)	Carbon (TgC)	Area (ha)	Carbon (TgC)	Area (ha)	Carbon (TgC)
indigenous forest	330 ± 65	16,100	5.4 ± 1.0	13,300	4.5 ± 0.86	14,000	4.7 ± 0.90
hardwood plantation	280 ± 77	2,300	0.64 ± 0.18	1,400	0.39 ± 0.11	3,100	0.87 ± 0.24
softwood plantation	250 ± 78	900	0.23 ± 0.07	970	0.24 ± 0.08	600	0.15 ± 0.05
FOREST TOTAL		19,400	6.3 ± 1.3	15,700	5.1 ± 1.0	17,700	5.7 ± 1.2
<i>% change in time interval</i>		<i>unknown</i>	<i>unknown</i>	-20%	-19%	+13%	+12%
<i>rate of change in time interval (Tg C/year)</i>			<i>unknown</i>		-0.11		+0.04

In order to compare carbon stocks, it was assumed that the distribution of ‘young’ and ‘old’ forest and plantation was uniform throughout the period. However, this assumption was not

necessarily robust. Assuming that there is little significant difference between 11 years of growth (1975-1986) and 14 years of growth (1986-2000), tree cover classes in the 1986 map can be stratified into ‘young’ and ‘old’ forest classes, based on change since 1975, which are equivalent to the ‘young’ and ‘old’ classes in the 2000 map. This allowed for age-distribution comparisons between 1986 and 2000 (Table 8) that revealed a large inconsistency in the hardwood plantation class: 70% of hardwood plantation area was ‘young’ in 2000, but only 22.% was ‘young’ in 1986. By artificially lowering the amount of carbon attributable to hardwood plantations in 1986, the assumption of the 2000 age distribution in all years may have inflated the 1986-2000 carbon storage increase by roughly 50%. Assuming that 11 year and 14 year age stratifications are equivalent, carbon storage would have only increased by 0.4 Tg C since 1986 as opposed to 0.6 Tg C.

Table 8: Comparison of carbon storage change from 1986 to 2000 using age stratified carbon density averages

Tree cover class	Age	Mean carbon density (Mg c/ha)	1986				2000			
			Area (ha)	Proportion of class total (%)	Carbon (TgC)	Proportion of class total (%)	Area (ha)	Proportion of class total (%)	Carbon (TgC)	Proportion of class total (%)
indigenous forest	old	360 ± 63	12,400	93%	4.4 ± 0.57	96%	12,400	89%	4.4 ± 0.57	94.3%
	young	170 ± 78	1,000	7%	0.16 ± 0.02	4%	1,600	11%	0.27 ± 0.03	5.7%
hardwood plantation	old	370 ± 90	1,100	78%	0.41 ± 0.01	85%	900	29%	0.34 ± 0.01	39.6%
	young	240 ± 71	300	22%	0.07 ± 0.00	15%	2,200	71%	0.53 ± 0.02	60.4%
softwood plantation	old	290 ± 82	500	50%	0.13 ± 0.00	55%	300	44%	0.08 ± 0.00	52.2%
	young	210 ± 75	500	50%	0.11 ± 0.00	45%	400	56%	0.07 ± 0.00	47.8%
FOREST TOTAL			15,700		5.3 ± 0.61		17,700		5.7 ± 0.68	
% change in time interval							+13%		+8.0%	
rate of change							+150 ha/year		+0.03 Tg C/year	

Estimates of carbon storage in 1975 and 1986 may have been further underestimated by assuming plantations in all years had species compositions similar to those seen in 2000. The Forest Department plantation register indicated that a greater proportion of high carbon density indigenous hardwood species were planted before the late 1980s and that a higher planting rate of low carbon density *Eucalyptus saligna* ensued in recent years (Kakamega Forest Department, 2003). However, incomplete documentation of plantings and clearings prevent quantitative assessment of plantation composition. It appears likely that the loss of a more carbon rich hardwood plantation area between 1975 and 1986 resulted in greater carbon losses and that the

increase in hardwood plantation in 1986-2000 recouped less of this decline than these necessarily rough calculations suggest.

4. Discussion

4.1 Sources of uncertainty

Large uncertainties in estimating carbon storage are one of the arguments posited in opposition to carbon trading projects that involve land cover change (Goetze, 1999). The precision of the results of this study, and hence the ability to adequately compare carbon storage values between land cover classes and over periods of time, were primarily limited by the large heterogeneity within land cover classes. Adjustments made to account for buttressed trees and variations in wood densities also contributed to the uncertainty, but to a far lesser degree. Adjustments did alter resulting means by up to 15% and without extensive destructive tree sampling, the accuracy of these adjustments will remain unspecified. The uncertainties found reflect not only the need to use a sampling strategy that effectively captures the variation in forest structure, but also in the need for more information about the structures of tropical tree species and the patterns of tropical forest growth, particularly in Africa.

Ideally land cover stratification and sampling intensity within strata should reflect the variation in carbon storage between classes and heterogeneity within a class (MacDicken 1997). However, the degree of stratification must also depend upon the ability of the classification technique to discern between classes and the ability to quantify the area of each land cover type. In this study, land cover classification was limited by the sensitivity of satellite imagery and of the interpretation method (Rogo et al. 2003) used to discern between different types of tree cover. This strategy forced the grouping of both discrete plantations of different species found to have distinctly different carbon densities and of forest patches of various ages and levels of disturbance. Lacking another method to quantify the areas of various land cover classes within the time available, this coarse classification had to be utilized.

Although relatively high levels of uncertainty in plantation carbon estimates may be more or less unique to this study, difficulties in establishing an adequately representative mean carbon densities for tropical rainforests have been well documented (Brown et al, 1995; Hall et al., 2001; Houghton et al., 2001; Keller et al., 2001; Chave et al., 2003). While plot and sample sizes

should be chosen based on the scale of heterogeneity of a forest (Chave et al. 2003, Hall et al., 2001; Houghton et al. 2001, Keller et al. 2001, MacDicken 1997), the actual spatial scales of significant variations in carbon density in tropical rainforests can range from single hectares to hundreds of thousands due to factors ranging from elevation and annual temperature to individual tree falls and microclimates that can be difficult to predict or remotely sense (Brown et al., 1995; Brown & Gaston, 1998; Laurance et al., 1999; Harms, 2001; Chave et al., 2003).

However, several studies suggest that rainforest carbon density distributions are largely determined by the presence of large trees (Chave et al. 2003, Keller et al 2001, Brown et al. 1995, Clarke & Clarke 1996), indicating that prior knowledge of the distribution of large trees can help guide choices of plot and sample size. Results suggest that this may be the case in Kakamega: the presence of large trees ($\text{dbh} \geq 50 \text{ cm}$) predicted over 50% of the variation in plot carbon densities ($p < 0.05$). Approximately 73% of indigenous forest plots contained at least one tree with $\text{dbh} \geq 50 \text{ cm}$, and while these trees only represented 5% of all the trees in the plots, they contributed 46% of the tree biomass. Plots with at least one very large tree ($\text{dbh} \geq 70 \text{ cm}$), 49% of the indigenous forest plots, had an average carbon density that was 2.5 times larger ($p < 0.05$) than plots that did not contain very large trees. If the measured sample did not capture the actual distribution of large trees in the forest, the precision and possibly the accuracy of the carbon density estimate will have been compromised. It appears not knowing how the distribution of these trees is stochastically, ecologically, and/or anthropogenically driven provides a large source of uncertainty.

The skewed distribution tree carbon density among plots (Figure 1a and b) is similar to the distribution found by Chave et al. (2003) when using plots of the same size (20x20m) to divide up a 50 ha block of moist tropical forest in Panama. Chave et al. (2003) and Keller et al. (2003) suggested that skewed distributions of plot carbon density the result of the lowered probability of capturing a very large tree in small plots, and found that increasing plot sizes produced a normal distribution around the true mean of an area that had been completely sampled. Smaller plots necessitate a greater number of plots to accurately assess the mean with any certainty. Nevertheless, without pilot data on the spatial distributions of forest gaps, very large trees, species distributions, or biomass density in Guineo-Congolian rainforests, it is impossible to accurately determine the magnitude of sampling error introduced into the estimated mean carbon density in the indigenous forest. Aware of possible errors of the mean, an IDW

nearest neighbor interpolation was also used to calculate carbon storage in the indigenous forest and thereby avoid extrapolating an inaccurate value over a large area and ignoring patterns of spatial variation. However, interpolation produced the same value as the application of the calculated average. If it is any indication of the probability of accuracy, the mean aboveground biomass for indigenous forest was found to be 400 ± 72 Mg/ha (200 ± 36 Mg C/ha), which is well within Brown and Gaston's (1995) modeled potential aboveground biomass of 412 Mg/ha for African lowland moist forest.

4.2 Carbon storage potential

Iverson et al. (1993) suggest two methods of assessing opportunities for increasing carbon sequestration: “the carbon store approach,” in which the total amount of carbon stored in a region is increased by increasing the area covered by a carbon dense cover type, and the “carbon sink approach,” in which the continuous annual growth rates of biomass in forests or plantations are increased. The results of this study reveal potential for further carbon sequestration in the Kakamega National Forest as a “carbon store,” as illustrated by the significant differences in carbon densities both between land cover classes and within them. Carbon storage can be altered by transitions between land cover types of different carbon density with Kakamega Forest, and this was seen in the land cover transitions between 1975 and 2000 which resulted in a net loss of almost 0.6 Tg C, if not more. In theory, carbon storage in the forest could be increased from current levels by at least this amount by restoring the historical land cover pattern. While this was not a longitudinal study, and hence not designed to assess biomass accumulation rates, the carbon density values found in mature plantations can also be used to indicate the potential for plantations to act as continuously accumulating “carbon sinks” if they are harvested and are re-planted.

Forest classified as ‘young’ in 2000, had significantly lower carbon density (170 Mg c/ha) than the average of forest classified as ‘old’ (360 Mg C/ha). This ‘young’ forest class constituted forest regenerating on areas previously under different use and did not represent young forest patches inherent in the successional mosaic observed in the ‘old’ forest class. Therefore, it is not unreasonable to assume that, if allowed to continue regenerating, the 1,600 ha area of ‘young’ forest could attain an average carbon density close to the average measured in

the 'old' forest. This would constitute a 0.3 Tg C increase in the total carbon storage (over an unknown period of time) without changing the area devoted to indigenous forest.

The heterogeneity seen in carbon storage within the 'old' indigenous forest itself may suggest potential for further increasing carbon density within this class by reducing human disturbances. While the carbon storage difference between visibly disturbed plots and plots with no obvious evidence of anthropogenic influence was fairly small, 30 Mg C/ha, it was significant ($p < 0.05$). Weak but significant, linear trends of increasing carbon density were also observed with increasing distances from roads and towns (Table 6). This may be the result of edge effects on natural rates of tree mortality, work in Amazonia by Laurance et al. (1997) suggest that such effects do not significantly influence carbon density beyond 100m from forest edges. Instead this lower carbon density is likely due to increased accessibility of these areas for extractive uses, especially considering that, on average, visibly disturbed plots were found closer to forest edges than undisturbed plots. Areas without obvious evidence of recent disturbances may also have been disturbed in the past, and have lower carbon storage density for this reason, providing further opportunity to increase carbon storage should they be able to recover.

The fact that old indigenous forest plots within 2km of a forest station, the center of operation for FD and KWS, were found to have much higher average carbon densities (690 ± 130 Mg C/ha) than those at greater distances (340 ± 31 Mg C/ha), could indicate the effectiveness of the forest patrolling and/or environmental education efforts that are based at these stations. This result may also be indicative of a distance threshold of these effects (significant differences were not observed at 3 km). However, this was not a longitudinal study and it is possible that the stations may have been originally sited in areas with higher carbon densities. This is fairly likely, seeing as the KWS National Reserve (in which the station resides) and the FD Nature Reserves located close to the station were purposefully located in less disturbed areas of the forest. However, neither the KWS management area nor the FD Nature Reserves had significantly different carbon densities to the rest of the forest, indicating that the distance from the stations may have subsequently played a role in determining forest carbon density beyond original site differences. If the drivers of the high carbon densities observed around the stations could be applied to larger areas, there may be the potential for increasing the amount of carbon stored in the current extent of the indigenous forest by up to 5.3 ± 2.0 Tg C.

Plantation areas provide an opportunity both for increasing carbon sequestration in Kakamega through the carbon store approach and possibly by creating what Iverson et al. (1993) refer to as “limited sinks.” Softwood plantations were found to have significantly lower average carbon density than either indigenous forest or hardwood plantation and mature *Eucalyptus saligna* plantations had almost half the carbon densities of mature plantations of the other planted hardwoods. Without changing the amount of land dedicated to plantation, carbon stores could be increased by dedicating plantation land to species with higher carbon densities. Lacking specific information of current species allocations of current plantations it is difficult to calculate the possible gains; however, if all softwood plantation areas in the year 2000 had the average carbon density of the sampled hardwood plantation area, carbon stocks could be increased by 0.02 Tg C. Replacing these with indigenous forest would increase the stock by a similar amount, 0.06 Tg C. However, Kakamega’s plantations of non-indigenous species are harvested in rotation, and can therefore create a *carbon sink* as the growing trees constantly sequester carbon. Considering the high fuelwood demand in Kakamega, it is likely that most of plantation biomass will be burned, but if fuelwood plantations are harvested and re-grown at a sustainable rate, plantation rotation areas can be assumed to store half the carbon of a mature stand (Schroeder, 1992). Half the carbon density of a mature stand of *B.javonica* (180 Mg C/ha), would still result in higher carbon storage efficiency than land with half the carbon storage density of *E.saligna* (90 Mg C/ha).

There is some opportunity to actually expand forest and plantation cover within the Kakamega boundaries in grasslands and degraded forest areas. It was assumed that grasslands and open forest areas do not store significant amounts of carbon as they lack significant tree cover. However, it was found that significant amounts of carbon are stored in forest soils, suggesting that these areas could store up to 100 Mg C/ha. Nevertheless, it was found that soil carbon did increase with increased plot aboveground biomass and preliminary results by Awiti (unpublished) suggest that forest soil’s carbon content declines drastically after 15 years of cultivation partially due to the lack of organic inputs from forest litter, justifying the assumption of insignificant carbon storage in grasslands although further study is needed to verify this. Significant forest regeneration was seen in grasslands in 1986-2000. Extrapolating this trend such that all grasslands (1,547 ha) became closed forest yields 0.5 Tg C increase in storage. However there has been speculation that some of the grasslands are maintained distinct from the

forest by edaphic conditions (Kokwaro, 1988) and the high demand for grazing land might also ensure their longevity.

4.3 Management options for carbon storage projects

Given the high carbon storage density of Kakamega's indigenous forest, a carbon offset project aimed at preventing further loss of the forest would be more lucrative and more instantaneous than a reforestation or plantation project. However, as the land is already protected as national forest and there was a net gain in indigenous forest cover since 1986, it might be difficult to prove that a deforestation prevention project is having an effect that would otherwise have not occurred, a necessary condition at least for CDM projects (Brown et al. 2000).

It has been demonstrated that a carbon storage increase in the range of 0.6 Tg C could be reasonably achieved by shifting land cover patterns. This is within the range of other internationally funded reforestation and forest management based carbon-offset projects seen in Belize, Malaysia, Mexico, and Russia (World Resources Institute, 2002). Indeed, even with speculated carbon prices currently at a low (\$3-5/ ton C), a carbon storage project of this size could bring in as much as \$3 million over the course of full forest regeneration or plantation growth. Even if it would take 50 years to store this carbon, an annual \$60,000 is larger than the current annual operation budgets of the Kakamega Forest Department, KWS, or any community conservation organizations in the area.

While opportunities do exist to increase the amounts of carbon stored in Kakamega's indigenous forest area, the management strategies that would produce this effect, need to be carefully considered. While the highest carbon density values in indigenous forest were found within 2 km of the forest stations, the implications of this result are not certain. The ban on extractive use in the KWS National Reserve has not resulted in forest carbon densities or grassland regeneration rates that are discernibly greater than the rest of Kakamega in the eighteen years since the change in management took effect. Indeed the FD Nature Reserves, in which extractive uses have been illegal since 1967, did not have significantly different carbon densities from the rest of the forest.

Planting indigenous trees species would increase the area of land under a high carbon density cover, but this would not guarantee overall increases in carbon stocks. Local environmental and charity organizations, such as the Kakamega Environmental Education

Project, have already sponsored the plantation of indigenous species in a few open areas. However, these trees could not be legally felled for fuelwood and the replacement of open areas by plantations would also decrease land available for stock grazing. If done on a large scale without simultaneously taking actions to meet the resource needs of the surrounding community, such plantations may lead to increased illegal wood harvesting within the forest or in surrounding areas, resulting in ‘leakage’ (Brown et al, 2000) of the carbon offset. Completely replacing the fast growing, low density plantation species like *E.saligna*, *P. patula*, or *C.lustanica*, with high density, slow growing timber species like *B. javonica* could similarly result in leakage. It is difficult to speculate about the magnitude of such leakage. As harvesting of trees in the indigenous forest is illegal, while its occurrence has been confirmed, its magnitude is likely to remain largely unquantified without significant monitoring effort. It may be possible to avoid leakage through investing carbon offset profits in projects such as fuel efficient stove installations that would ease fuelwood demand.

These concerns illustrate the difference between what Iverson et al. (1993) refer to as ‘technical’ and ‘actual’ suitability for carbon sequestration and highlight the need to take into account the opportunity costs of various management strategies on both local and national levels. One management strategy that may be able to balance local resource needs and deforestation prevention is the ‘Biosphere Reserve’ model: a natural reserve area is divided into a core zone in which no extractive uses are permitted surrounded by zones for extractive use by local communities which directly participate in planning the sustainable management of this area (UNESCO, 2002). In fact, a similar strategy was proposed by Kenya Indigenous Forest Conservation Program (KIFCON) in 1993 as a result of in depth local socio-economic assessments and discussions with the forest’s managing bodies (Sharp, 1993).

Table 9: Assessment of Kakamega carbon storage under KIFCON suggested management scenario

Cover type	Area (ha)	Carbon density at 30 yrs (Mg C/ha)	
Non-extractive forest	12,070	old indigenous forest	356
Used forest	6,600	visibly disturbed indigenous forest	203
10 yr plantation	2,100	<i>E. saligna</i> (half of projected density for mature stand)	94
30 yr plantation	3,200	<i>C. lustanica</i> (half of projected density for mature stand)	108
TOTAL STORED			6.2 Tg C

KIFCON suggested that both the KWS Reserve and a core region of the Forest Department forest should be reserved for strictly non-extractive use, while an 11,900 area around forest margins be available for extractive uses of natural forest as well as for plantations, to be managed co-operatively by the FD, KWS, and local community groups in the surrounding villages (Sharp 1993). To get a rough estimate of Kakamega's carbon stocks under such a strategy, the carbon densities found in this study were applied to areas suggested for the different land cover classes as calculated by scaling up KIFCON's suggested plantation needs of one sub-location, to the 15 village sub-locations around the forest (Table 9). This calculation suggests with 30 years that Kakamega's carbon stock could increase by 0.47 Tg C over current storage under such a management plan. The increase could be even greater if enhanced protection of the core zone increased its average carbon density, a possibility suggested by the high carbon storage values in the well monitored areas around the forest stations.

This study illustrates that there is potential to increase carbon sequestration in the Kakamega National Forest at a scale that is economically, and perhaps ecologically, significant for the region. However, further research on the structure of African rainforests, local feasibility assessments of forest management options, and institutional capacity building are all necessary if forestry based carbon offset projects are to become a meaningful part of sustainable forest preservation in Africa.

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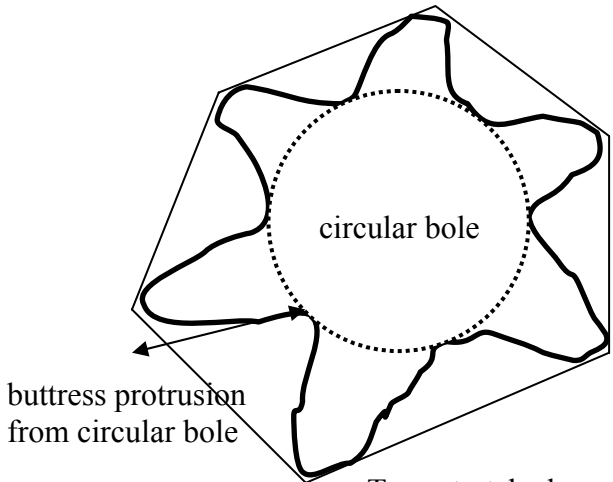
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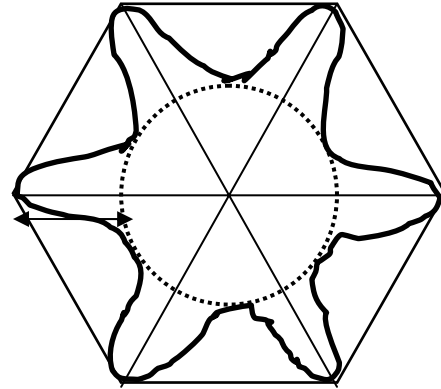
APPENDICES

A. Buttress correction factor for tree diameters measured over buttresses

Cross section of buttressed tree bole



Tape stretched over buttress protrusions such that the actual measurement is the polygon perimeter.

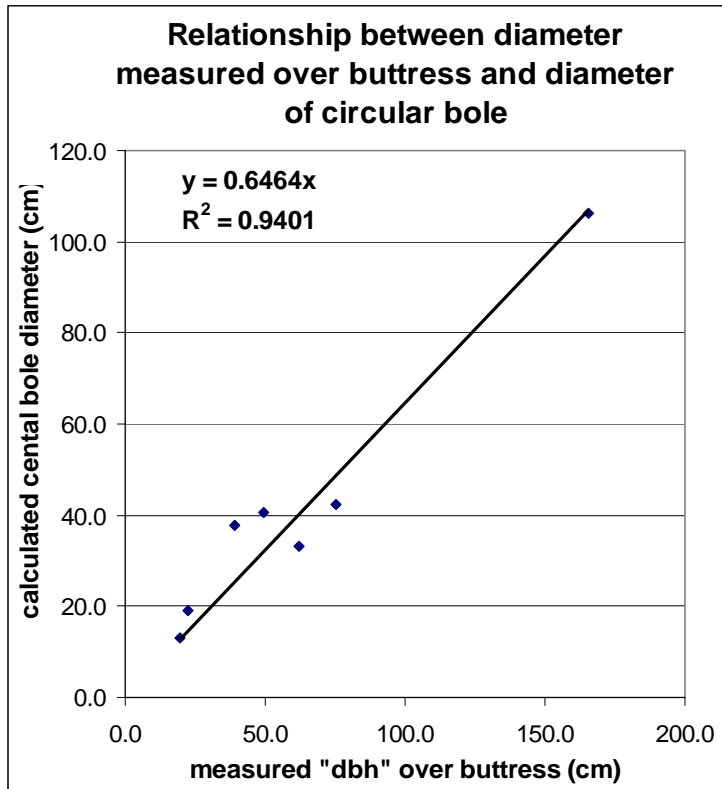


Idealized configuration, in which buttress protrusions of equal size (mean protrusion size measured on tree) form a regular polygon around the circular bole, used to calculate the diameter of the circular bole.

By assuming the idealized regular polygon shown on the right hand side of the figure, the radius of the circular bole was calculated using the law of cosines. Linear regression between measured diameter and circular bole diameter was used to find a correction factor.

Sample calculation of diameter correction factor: *Ficus spp.*

Measured dbh (cm) <i>reading over buttress</i>	Number of buttresses	Average buttress protrusion (cm)	Average distance between buttresses (cm) <i>side length of idealized polygon</i>	Diameter of circular bole (cm)
19.6	3	1.0	13.0	13.0
39.3	4	2.6	30.5	37.9
22.7	3	1.0	18.3	19.2
49.5	5	6.5	31.4	40.5
62.1	6	9.4	26.0	33.2
75.2	6	13.7	34.8	42.3
165.7	9	28.8	56.1	106.4



Diameter correction factors for buttressed species

Species	Samples	Diameter correction factor
<i>Ficus spp.</i>	7	0.65
<i>Aningeria altissima</i>	4	0.5
<i>Celtis spp.</i>	4	0.64

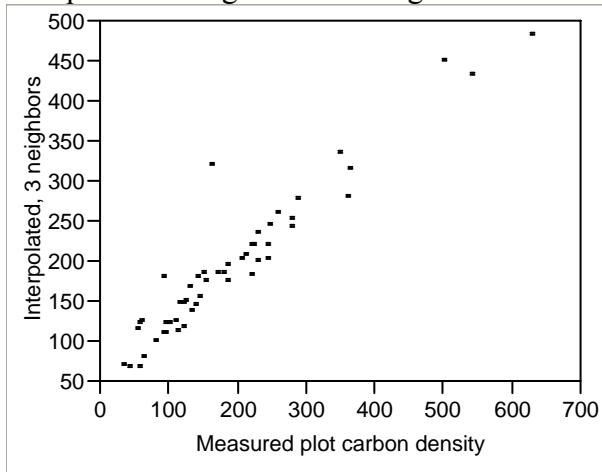
B. Regression equations used to calculate tree biomass

Species	Equation	Source
Moist tropical hardwoods (for dbh < 160 cm)	$\text{kg biomass} = \exp\{-2.134 + 2.530 \cdot \ln(\text{dbh cm})\}$	Brown, 1997 (FAO)
Moist tropical hardwoods (for dbh \leq 160 cm)	$\text{kg biomass} = 42.69 - 12.800(\text{dbh cm}) + 1.242(\text{dbh cm})^2$	Brown, 1997 (FAO)
Lianas	$\log(\text{kg biomass}) = 0.12 + 0.91 \log(\text{stem basal area})$	Putz, 1983
<i>Eucalyptus saligna</i>	$\text{kg biomass} = 0.167 \cdot (\text{dbh cm})^{2.21}$	Specht & West, 1998
<i>Pinus patula</i>	$\text{kg biomass} = \exp\{-1.170 + 2.119 \cdot \ln(\text{dbh cm})\}$	Brown, 1997 (FAO)
<i>Cupressus lustranica</i>	$\text{kg biomass} = 4.5966 - 0.2364(\text{dbh mm}) + 0.00411(\text{dbh mm})^2$	Monteith, 1979

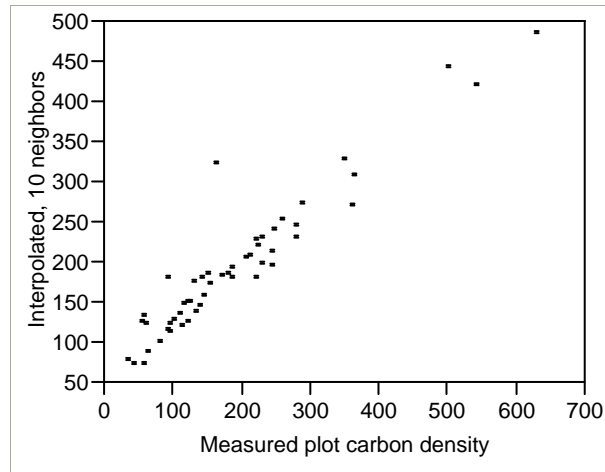
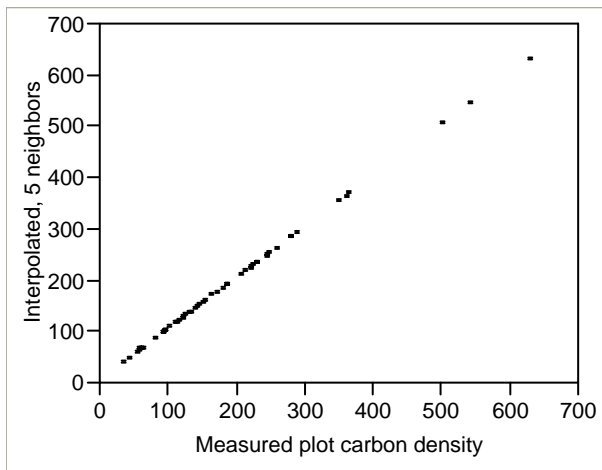
C. Selection of most appropriate IDW nearest neighbors interpolation method

Measured carbon density (Mg C/ ha) in each indigenous forest plot was graphed against the value predicted for the grid cell containing that plot in the inverse distance weighted (IDW) interpolation surface:

Interpolated using 3 nearest neighbors IDW



Interpolated using 5 nearest neighbors IDW (deemed best fit)



Interpolated using 10 nearest neighbors IDW