Preliminary Assessment of Carbon Storage & the Potential for Forestry Based Carbon Offset Projects in the Arabuko-Sokoke Forest

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Acronyms

AGB	Aboveground biomass – mass of plant organic matter occurring above soil surface, not roots
ASF	Arabuko-Sokoke Forest
ASFGA	Arabuko-Sokoke Field Guides Association
ASFCMP	Arabuko-Sokoke Forest Conservation and Management Project
ASFMT	Arabuko-Sokoke Forest Management Team
BGB	Belowground biomass – dry root mass, mass of plant organic matter occurring below soil surface
CDM	Combined Development Mechanism (CDM), Kyoto Protocol Article 12, allows industrialized nations to receive certified emissions reductions credits (CERs) for funding greenhouse gas emission reduction projects in developing nations
CER	Certified Emission Reduction credit, issued to a nation, industry, or company that funds a CDM project indicating that a reduction/offset of GHG emissions occurred as a result of the project, the credit can be used towards achieving their GHG reduction quota or sold to another party
COP	Conference of the Parties, all nations that have ratified the Kyoto Protocol
Dbh	diameter at breast height
DIFAAFA	Dida Forest Adjacent Area Forest Association
FADA	Forest Adjacent Dwellers Association
FD	Kenya Forest Department
GHG	greenhouse gas, a gas which prevents heat from escaping the earth's atmosphere (CO_2, CH_4, N_2O, CFC, PFC, etc)
GIS	Geographical Information System, digitized maps containing spatially explicit data (data linked to spatial coordinates such as latitude and longitude)
GPS	Geographic Positioning System, system for determining geographic coordinates for point locations in the field
ICIPE	International Center for Insect Physiology and Ecology
KEFRI	Kenya Forest Research Institute
KIFCON	Kenya Indigenous Forest Conservation
KWS	Kenya Wildlife Service
NK	Nature Kenya
UNFCCC	United Nations Framework Convention on Climate Change
95 % CI	95% confidence interval of an estimated value (measure of uncertainty)

Conversions

*"***C***" denotes that a measurement refers to an amount of carbon*

1 t (metric tonne)	=		**1Mg**		=	**1,000 kg**
1 Gt	=	**1 Tg**	=	**1,000,000 Mg**	=	**1,000,000,000 kg**

Abstract

Emerging markets for carbon emission offsets may offer developing nations such as Kenya with added funding sources for reforestation and forest protection efforts. Rapidly rising atmospheric carbon dioxide levels have been linked to global warming and climate change. In an effort to mitigate this, there have been a number of internationally backed projects that offset carbon dioxide emissions by increasing storage of carbon in terrestrial pools. Projects that involve reforestation, afforestation, and deforestation prevention increase terrestrial carbon stocks, decreasing atmospheric CO_2 stock. Having ratified the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) in 2005, Kenya can now participate in the UN sponsored carbon market, as well as voluntary carbon markets.

Kenya is in need of reforestation and forest protection activities. Forest loss means loss of many valuable ecosystem services such as erosion protection, soil quality maintenance, microclimate stabilization, water filtration, fuelwood and other forest product provision, species habitation, etc. Much of Kenya's indigenous forest has been degraded or cleared over the past century and high rates of loss continue with 93,000 ha cut in the last decade (FAO, 2001). It has been estimated based on biophysical and climactic features, that Kenya has the potential to double its current aboveground biomass (Brown & Gaston, 1995), meaning that Kenya could at least double its storage of carbon in vegetation and soils.

The Arabuko Sokoke Forest (ASF) is one of Kenya's most biodiverse forests and the largest remaining fragment of East African Coastal dry forest (ASFMT, 2002). While it is now a protected area, it has been subject to significant anthropogenic disturbance from past sawmilling of commercial timber as well as continued logging and subsistence resource extraction. This study aimed to assess the current carbon stock in ASF and the potential for carbon stocks to be increased through activities that could receive funding through existing carbon markets.

It was found that carbon densities in ASF's indigenous forest types (Brachystegia forest, Cynometra forest, 'mixed forest') ranged from 53-80 Mg C/ha. The total estimated carbon stock for ASF in 2004 was 3.0 Tg ± 0.2 Tg C. Evidence of recent illegal logging of trees of all sizes was observed throughout the forest, although more frequent near forest edges, roads, and guardposts. Areas with tree stumps were found to have lower carbon densities on average than those areas without. Improved forest management techniques that prevent continued anthropogenic disturbance and allow natural regeneration could increase carbon stocks in ASF by as much as 0.40 ± 0.2 Tg C. A carbon emission offset this size could be worth roughly $1.6 million. However, the slow growing nature of indigenous dry forests and the current lack Kyoto Protocol sanction for improved forest management as a carbon offset mechanism are barriers to attracting a carbon driven investor.

The recently gazetted Madunguni Forest, which abuts ASF to the north, was seen to have lost 86% of its closed forest and 20,000 Mg C between 1992-2004. Reforesting this area and facilitating tree planting on communal or individually owned land would provide carbon stock increases in a shorter time scale. Planting of agroforestry and fuelwood species would also provide resource and income alternatives to local communities, create carbon stores and potentially carbon sinks, while removing some pressure on the indigenous forest.

This report is meant to be relevant to both those experienced in issues of carbon storage and forestry and those without background in the area. It is also written for both those familiar with ASF and its history and those unfamiliar with the area. Parts 1 and 2 contain introductory background information on these topics, but ***further reading and resource suggestions*** are listed in *Appendix E.*

Part one gives a brief description of the link between land cover change and global climate change, an introduction to international climate change mitigation policy such as the Kyoto Protocol's Combined Development Mechanism (CDM), and a summary key issues regarding Kenya's potential to participate in the carbon trading market through forestry and land-use/land-cover change projects.

Part two is an introduction to the biophysical conditions, historical and current managerial systems, and extractive forest uses in the Arabuko-Sokoke Forest.

Part three describes the methodologies used to estimate the current carbon stock in Arabuko Sokoke Forest based upon mean carbon densities (amount of carbon per unit area) in vegetation, litter, and soils for different forest types. This includes descriptions of tree biomass estimation, lab techniques, and remote sensing methods used to map cover types.

Part four provides the results of the carbon stock assessment, carbon densities of various forest cover types sampled, and an assessment of the impacts of cover change and anthropogenic disturbances on current carbon stocks.

Part five assesses some basic scenarios for increasing future carbon stocks in ASF. These are preliminary assessments to be seen as examples for designing specific carbon stock project activities.

Part six makes recommendations for continued monitoring activities and for using agroforestry in ASF's adjacent area to increase carbon storage.

1. Introduction

Dry tropical forest is the most widely distributed habitat type in the tropics (Jaramillo et al, 2003), covering 42 % of all tropical vegetation (Murphy & Lugo, 1995). Although dry forests typically have lower biomass densities than moist or wet forests, the large areas they cover mean they store significant amounts of biomass carbon. These ecosystems have become increasingly threatened by human utilization. A greater proportion of dry forests have been degraded or cleared than moist forests (Mooney et al 1995; Robertson et al., 199-; Jaramillo at al. 2003). **Land cover change** from tropical dry forest and savanna to agricultural and urban areas can result in significant declines in total system carbon storage through cutting and burning of aboveground biomass, loss of forest litter additions to the soil carbon pool, and an increase in carbon releases from soils through tillage (Detwiler & Hall, 1988; Woomer, 1993). Releases of ecosystem carbon increase the **carbon dioxide (CO_2)** concentration in the atmosphere, promoting **global climate change** (Houghton, 1997).

Kenya's dry coastal forests have largely been cleared for settlement and the few remaining fragments have been subject to intensive selective logging. The Arabuko Sokoke Forest (ASF), a tropical dry forest in Kenya's Coast Province, is the largest remaining fragment of coastal forest in East Africa. An internationally recognized biodiversity hotspot, it ranks eighth in the world for biodiversity and first for density of endemic species (Myers et al, 2000). It supports over 600 plant species, 50 of which are considered rare; 230 bird species, of which 6 are globally threatened; and 52 mammal species, of which three are globally threatened (ASFMT, 2002). While its biodiversity value and its subsistence uses to the community have been studied and taken into account in the current management plan (ASFMT, 2002), its role as a carbon store has not been quanitified. This study aims to measure this global ecosystem service for ASF and provide a preliminary assessment of the potential to increase carbon storage in the area and perhaps attract carbon trading funds to aid forest restoration and management efforts.

1.1 Carbon, the Kyoto Protocol, & the Combined Development Mechanism

a. Land cover change and the greenhouse effect

Concerns about human driven global warming and deforestation trends have driven scientific efforts to quantify the role of forests in the global carbon cycle and political efforts to make forest preservation more socioeconomically attractive (Brown, 1997; Houghton, 1997; Watson et al., 2000). Since the Industrial Revolution, the concentration of **CO_2** in the earth's atmosphere has steadily increased at a rate faster than any changes seen in the past hundred thousand years. Human activities that produce atmospheric carbon include:

- fossil fuel (petroleum, coal) burning
- biomass (wood, vegetation) burning
- land cover changes (such as deforestation)

Because carbon dioxide gas traps heat in the earth's atmosphere like a blanket (the **greenhouse effect**), significant increases in atmospheric carbon are believed to impact the earth's climate. Several other gases, such as methane (CH_4) and nitrous oxide (N_2O), also prevent heat from leaving the atmosphere. These gases are also produced by human activities;

however, due to high production levels, carbon dioxide is thought to have the greatest effect on the climate (Houghton, 1997). Climate models predict that the augmented concentration of these **greenhouse gases (GHGs)** will increase global average temperatures, leading to:

- changed local weather patterns
- increased numbers of storms, floods, and droughts
- global sea level rise

It is believed that **developing nations** of the subtropics will suffer much of the burden of these changes due to:

- increased aridity and loss of water resources
- loss of agricultural capacity and increased erosion
- loss of biodiversity and key ecosystems and/or reduced ecosystem function
- increased ranges of vector born diseases such as malaria

(Figueres, 2002)

While the majority of the recent increase in atmospheric carbon can be attributed to fossil fuel burning, it was estimated that land-use change, primarily the loss of forest cover, was responsible for 20-30% of the net increase over the last 20 years (Houghton, 1997). Plants remove carbon dioxide from the atmosphere (**carbon sequestration**) and use this carbon to build their body structures (their biomass) during photosynthesis. As a result, 50% of a plant's dry biomass is comprised of carbon. Forests, with their high density of woody vegetation, have much greater biomass than other vegetation cover types and hence store more carbon. Forests also maintain large stocks of carbon rich organic matter in their soils due to constant litter and deadwood production and relatively slow decomposition. Therefore, forests store large amounts of terrestrial carbon per unit area (high **carbon density**). In addition to storing carbon, forests may also act as **carbon 'sinks'** if the rate of carbon sequestration from plant growth exceeds the rate by which biomass carbon is returned to the atmosphere through natural decomposition and/or biomass burning.

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 and soil is released into the atmosphere and a potential carbon sink is lost. Globally, an estimated 13 million hectares of tropical forest was lost each year to deforestation (FAO, 1999) emitting between 5.6 and 8.6 Gt of carbon (Houghton at al., 1995). Preventing further deforestation and encouraging forest regeneration not only preserves biodiversity and other local ecosystem services, but may also mitigate global climate change by preventing the carbon stored in trees and soils from being released into the atmosphere. In addition, **reforestation** and **afforestation** (forest growth in an area not previously forested) activities could attract funds for sustainable development from emerging international carbon markets.

b. International treaties and carbon emissions offset trading

In an effort to mitigate global climate change, 154 nations, including Kenya, signed the **United Nations Framework Convention on Climate Change (UNFCCC)** in 1992. **Party nations** (nations which have *ratified*, accepted responsibility to implement, the convention) agreed to produce **national GHG emissions inventories**, assessing contributions from industrial and agricultural sectors, transportation, energy production, land cover change, and forest losses and growth within their borders. Knowledge of carbon storage trends is used to design climate models that forecast future climates and to identify key areas for emission reduction.

The UNFCCC acknowledges that industrialized nations hold the greatest responsibility for emitting greenhouse gases, while the developing world will suffer the brunt of the consequences. As a result, 41 listed **industrialized nations (Annex I)** were deemed responsible for reducing their collective GHG emissions. By 1997 the recommendations of the UNFCCC were consolidated into the **Kyoto Protocol** to provide a *'global action plan'* to implement GHG reduction activities (Figueres, 2002). The protocol entered into force in February 2005, binding industrialized parties to reduce their carbon emissions by the end of 2012 to levels below their estimated emissions in 1990.

Because atmospheric GHGs have global effects regardless of where they are released, in terms of the effect on the climate, it does not matter where emission reductions occur. In light of this, the Kyoto Protocol includes several *'flexibility mechanisms'* permitting industrialized nations to reduce global GHG emissions by investing in emission reduction activities in other countries, which is often more economical and efficient than taking emission reduction measures at home. One of these flexibility mechanisms, known as the **Combined Development Mechanism (CDM)**, Kyoto Protocol Article 12, party approved in 2000 and refined in 2001 (Marrakech Accords), allows industrialized nations to fund GHG emission reduction activities in developing nations in return for **certified emissions reduction credits (CERs)**. CERs help the industrialized nation achieve its emission reduction quota, while the funded projects promote less carbon intensive development in the developing nation and foster technology transfer. Such projects include the establishment of:

- forest regeneration activities
- timber plantations with sustainable harvesting rates
- energy efficiency improvements
- cleaner/renewable energy production and industrial manufacturing methods

provided that these activities produce measurable net GHG emissions reductions that would not have otherwise occurred without the CER investment (**additionality requirement**).

The CDM is administrated by an **executive board** consisting of elected representatives from each United Nations regional group, two industrialized nation representatives, two developing nation representatives, and a small island state representative and receives guidance from the **Conference of the Parties (COP)** that consists of all nations that have ratified the Kyoto Protocol. To participate in the CDM, nations must:

- ratify the Kyoto Protocol
- show that participation is voluntary,
- establish a **National CDM Authority** to facilitate, evaluate, and approve CDM projects

Industrialized nations must also establish an emissions reduction target, a national GHG emission inventory, and an emissions reduction accounting system with which to purchase reduction credits.

To prove **additionality**, that a project reduces net GHG emissions beyond what would occur without the project, a **carbon baseline** (*predicted carbon storage and emissions without the project*) must be established specifically for the project area in the developing nation. A project predicted to feasibly reduce atmospheric GHGs must then be approved by the host nation's National CDM Authority and evaluated by an independent party for approval by the executive board. Internal monitoring and subsequent independent review will be required for the executive board to issue CERs.

In addition to the market for CERs, there is also a **voluntary carbon trading market** for bodies interested in funding carbon emission reduction or carbon storing projects even if they are not mandated to do so. These bodies include aid agencies, American companies, trust funds, and various NGOs. The United States, which produces 20% of global anthropogenic GHG releases (Figueres, 2002), has not signed on to Kyoto; however, several American states have independently chosen enforce limits on emissions and American industries have funded forestry projects to counteract their emissions.

1.2 Forest carbon storage projects and Kenya's potential

Several forestry activities can offset emissions of CO_2 to the atmosphere. **Afforestation and reforestation** (**A/R**) sequester carbon from the atmosphere and store it in tree biomass. **Deforestation prevention** and **improved forest management practices** *(low impact use plans, sustainable harvest rates, enrichment planting, etc*) reduce carbon emissions that would have otherwise occurred had the forest been cleared or over exploited. During the first emissions reductions commitment period of the Kyoto Protocol (2008-2012), industrialized nations can receive CERs for funding A/R projects under the CDM. To avoid creating incentives to clear more forest, CDM CERs will only be issued for reforestation of areas **cleared pre-1990**. While deforestation prevention and improved forest management are not currently accredited in the CDM, possibilities for such projects to receive carbon funding in the voluntary carbon market and in future commitment periods of Kyoto after 2012.

National utilities, private companies, and international consortiums have begun to invest in forestry based carbon offset and storage projects (examples in **Table 1**) with over 150 bilateral projects having been developed by 2000 (Bass et al., 2000). For example, the Electricity Generating Board (SEP) of the Netherlands founded the Forest Absorbing Carbon Emissions (FACE) project to sequester the carbon it emitted from burning fossil fuels. FACE has funded forestry projects in the Czech Republic, Ecuador, and Uganda (WRI, 2000). As seen in Table 1, the cost of implementing these projects generally did not exceed the trading price for carbon credits.

Forest carbon offset projects could indeed assist Kenya by supplying financial assistance and incentives to slow the rapid disappearance of its forests. Model-based assessments of vegetation carbon storage in Africa suggest great potential to increase carbon stocks: much of the area with the biophysical capacity to support carbon rich tropical forests is currently degraded or deforested (Brown and Gaston, 1995; Zang and Justice, 2001). Based on analysis of rainfall, topography, temperature, and soil, Brown and Gaston (1995) suggest that Kenya could double its aboveground biomass carbon, and the deforestation of 93,000 ha of the Kenya's closed forest in the past decade (FAO, 2001) clearly suggests possibilities for forest protection and reforestation projects.

One potential barrier to Kenya's participation is the large amount of information needed to initiate a carbon project. General models can identify lands that are **'technically suitable**' for carbon sequestration, areas that *could* support forest cover, but there is also need to determine which areas are **'actually available'** for such efforts (Iverson et al. 1993). Much of Kenya's area with the biophysical capacity to support forest is used for smallholder agriculture or is surrounded by dense populations with high resource needs. Assessment of local socioeconomic, political, tenure, and cultural factors of technically suitable areas helps ensure carbon storage activities can be achieved in a sustainable manner in these areas. A **carbon baseline** and **monitoring program** also need to be established, requiring more detailed forest inventories than currently exist for many African forests and carbon inventories of any agricultural/agroforestry systems involved. Fortunately to encourage tree planting on small available areas or by groups of individual landholders, the CDM board is working on a *simplified project procedures* for **small-scale afforestation or reforestation (SSC-A/R) projects** storing 8,000 Mg C or less per year.

Table 1 Examples of existing carbon emissions offset forestry projects

	Host country	Project location	Description	Approx. carbon storage (Tg C)	Approx. cost efficiency ($/Mg C)	International stakeholders and investors	Local partners	Source
Africa	Uganda	Bukuleba Reserve (residential agriculture & tropical forest)	pine and eucalyptus plantation on leased concessions	not given	not given	Tree Farms (company), Norwegian Afforestation Group	name not listed	World Rainforest Movement (2000)
	Uganda	Kibale National Park (tropical forest)	reforestation & preservation; indigenous species planted on degraded areas, protection	7.2	0.78	FACE (Dutch utility consortium), ClimateCare , Cooperative Bank	not listed (project includes local hire and management)	World Resource Institute (2002)
	Sudan & Benin	arid wooded savanna	tree protection, border planting	1 - 5	not given	UNDP, GEF, Near East Foundation	Range & Pasture Administration, Gov'ts of Sudan & Benin	FAO/ISRIC (2004)
	Tanzania	Kilombero District (residential agri with moist forest level rain)	pine and eucalyptus plantation on leased concessions	not given	3.50	Tree Farms (company), Tanzanian subsidiary	Sokoine University of Agriculture	FAO/ISRIC (2004)
	Tanzania, Uganda, India	various - rural residential agriculture	community agroforestry and on farm tree planting in farmer groups	3	not given	Tanzania/International Small Group Tree Planting (TIST), Clean Air Action (carbon credit broker - many investors)	2,600 groups in TZ, 66 groups in UG, 249 groups in India	TIST (2004)
Asia	Malaysia	(tropical forest)	reduced impact logging; local staff training, directional felling, harvesting plans, buffer zones	0.5	1.00	RIL Logging: New England Electric (NEES), Rainforest Alliance, COPEC	Innoprise Corp. (local timber concession holder)	World Resource Institute (2002)
	India	Rahtgaon & Handia Range Forests (dry deciduous forest)	forest protection, controlled extraction	0.5	15	USAID, Community Forestry International	Harda Forest Division	FAO/ISRIC (2004)
	India	Gudibanda Taluk (residential agriculture)	community planting of mango and jack fruit trees on farms	0.6	not given	Plan Vivo Trust Fund	Women for Sustainable Development (WSD)	FAO/ISRIC (2004)
	Malaysia	(tropical forest)	reduced impact logging	0.4	1.00	UtiliTree Carbon Co., Center of International Forestry Research (CIFOR), Rainforest Alliance	Forest Research Institute of Malaysia, Sabah Forestry Dept.	World Resource Institute (2002)
Latin America	Belize	Rio Bravo Reserve (tropical forest)	forest preservation; sustainable management, promote local alternative income projects to prevent forest clearing	5.0	0.52	UtiliTree Carbon Co., The Nature Conservancy, Wisconsin Electric Power Co., Cinergy Corp., Detroit Edison Co., PacifiCorp, etc (27 US utilities invested)	Programme for Belize, The Nature Conservancy	World Resource Institute (2002)

	Boliva	Noel Kempf Reserve (tropical forest)	forest preservation; extend the area included in the protected reserve	6.8	1.25	American Electric Power, Inc (AEP), The Nature Conservancy	Fundación Amigos de la Naturaleza (FAN)	World Resource Institute (2002)
	Costa Rica	CARFIX Reserve (tropical forest)	forest preservation; sustainable management, promote local alternative income projects to prevent forest clearing, includes sustainable timber plantations	2.0	2.73	CARFIX, MERINEM, Wachovia Timberland Investment Management	FUNDECOR (local NGO)	World Resource Institute (2002)
	Costa Rica	(tropical forest)	forest preservation	1.0	0.90	ECOLAND: Tenaska Washington Partners, Trexler & Associates, National Fish & Wildlife Foundation	COMBOS, MIRENEM, Council of the OSA Conservation Area	World Resource Institute (2002)
	Ecuador	(tropical forest)	reforestation	9.6	0.59	FACE (Dutch utility consortium)	not given	World Resource Institute (2002)
	Guatamala	Maya Biosphere Reserve (tropical forest)	reforestation and preservation; protection, promote agroforestry to prevent forest clearing	36.8	0.38	CARE, AES (Allied Energy Services Corp.)	not given	World Resource Institute (2002)
	Guatamala	(tropical forest margins)	promote agroforestry, sustainable timber harvest, and increased cultivation efficiency to prevent forest clearing	not given	not given	Scandanavian aid agencies: DANIDA (Denmark), NORAD (Norway), SIDA (Sweden)	Tropical Agriculture Research and Education Center (CAITE) (regional science & education NGO)	World Resource Institute (2002)
	Paraguay	Mbaracayu Conservation Area (tropical forest)	forest preservation; protection, promote agroforestry to prevent forest clearing	14.6	0.27	AES, The Nature Conservancy, FMB Foundation, USAID	not given	World Resource Institute (2002)
	Mexico	Chiapas (agricultural, highlands and lowlands ecosystems)	Community agroforestry and on farm tree planting	15.0	12.00	Plan Vivo Trust Fund, Edinburgh Center for Carbon Management (ECCM)	AMBIO cooperative , Mexican gov't., individual farmers	FAO/ISRIC (2004)
	Peru, Ecuador, Bolivia	Amazonia (tropical forest)	forest preservation; tenure and sustainable management by indigenous groups	70.0	0.30	AES, OXFAM	not given	World Resource Institute (2002)

There is concern that the carbon market will not direct funds to the relatively unmeasured African forests when competing with more intensively studied rainforests of the Neotropics (Goetze, 1999) and/or toward more easily measured monoculture plantations (World Rainforest Movement, 2000). There have been relatively few in depth carbon analyses of Sub-Saharan African indigenous forests even though they may account for one fifth of global net primary production (Cao et al., 2001). As well as the more extensive forest research, South and Central America also have a head start on setting up their National CDM Authorities and greater experience in determining what projects will and will not prove successful. Only a handful of projects have been attempted in Africa. Uganda and Tanzania have begun to participate with mixed success. The Kenyan Government has initiated a branch of **NEMA** (**National Environmental Management Agency**) to be the climate change and CDM authority, but has yet to finalize specific project approval guidelines or host a project.

Now that the Kyoto Protocol has come into force, economists predict rising prices for carbon credits (van 't Veld & Plantinga, 2004), but, as Annex I nations can only use CDM credits to account for 5% of their carbon emissions at most, the competition for limited available project funding is already intense. For example, the $33.3 million BioCarbon Fund, a product of the World Bank to finance carbon storing land-cover change projects, opened in May 2004 and had already received 130 proposals and closed itself to new applications by December 2004. It is clear that information gathering and capacity building will be needed for Kenya to take full advantage of the CDM and the process needs to be timely.

a. Concerns in measurement and monitoring indigenous forests

Refining estimates of carbon storage in tropical African forests, while challenging, is crucial to understanding how maintaining or enhancing forest cover could be used to mitigate climate change and where Africa can best take advantage of the carbon market. Measurement methods for carbon storage in tropical forests are still evolving. Carbon storage estimates for African forests have been primarily based on extrapolation from a few forest surveys and inventory data from the United Nations Food and Agricultural Organization, the FAO (Brown and Gaston, 1995; Cao et al. 2001). Many existing forest inventories in Africa completed by government agencies have typically focused on commercially valuable trees which can underestimate carbon storage by ignoring high densities of small trees and/or noncommercial species (Cao et al. 2001).

Remote-sensing techniques can help determine the area of forest cover, but in **field surveys** are still needed to account for the range of biomass densities in closed canopy forest. Due to the high spatial variability typically found in tree species, tree sizes, and stem densities in tropical forest, it can be difficult to produce a reliable estimate of average carbon density for a forest without high sampling intensity: large numbers and/or sizes of sampled areas (Brown et al, 1995; Hall et al., 2001; Houghton et al., 2001; Keller et al., 2001; Chave et al., 2003). For a carbon-trading project, the frequency and intensity of forest monitoring impacts the amount of carbon sequestration that can be accounted for at the necessary precision for the sale of CERS.

Currently funded forest protection/regeneration projects show that suitable carbon stock estimates for natural forest can be achieved at non-prohibitive cost. Economic models developed to balance monitoring costs with carbon gains suggest **long-term average monitoring**, in which monitoring is performed every 5-10 years until a **stable long-term average** has been attained is often the most economical option in modeled forestry systems (Robertson et al., 2004). If carbon monitoring can be combined with other inventories funded by other means more frequent monitoring should be feasible.

b. Concerns in project design, management, & sustainability

Forestry carbon projects provide opportunities for improvements in:

- land cover management
- local employment
- environmental conditions/ ecosystem services
- biodiversity protectiong
- technology/information transfer

However, none of these are guaranteed benefits. For a forestry project to earn carbon credits, it must reduce or prevent carbon emissions that would have otherwise occurred. This doesn't ensure the project will be environmentally or socio-economically beneficial to the host nation or forest adjacent community.

Projects that do not address local resource needs and cultural concerns can prove difficult to maintain. Part of ensuring that a project actually increases net global carbon storage is accounting for project 'leakage.' **Leakage** refers to a loss of carbon storage outside of the project area as a result of project activities. For example, if a forest regeneration project prohibits adjacent communities from harvesting wood in the project area without addressing their wood needs, they may simply fell more trees or clear forest in another area. This will reduce the amount carbon stocks in this other area and reduce the overall ***net* carbon benefit** of the project. Local inhabitants under threat of resource alienation may resist project implementation. As a result, many successful projects have incorporated:

- alternative employment (not based on forest resource extraction)
- agroforestry and forest timber replacement
- agricultural and wood-use efficiency promotion.

Carbon trading profits can help fund these project components, which may subsequently produce their own financial returns. Sustainable projects that include poverty alleviation attract socially responsible corporate investors, who comprise much of the current carbon market, and generally have lower the risks of project failure (Figueres, 2002).

Two carbon-offset forestry projects in Uganda illustrate this. One project, which established pine and eucalyptus plantations on marginal agricultural lands, resulted in the eviction of 8,000 project area inhabitants without due compensation or firm evidence of substantial carbon benefits (Eraker, 2000 a; Eraker, 2000 b; World Rainforest Movement, 2000). After arson and destructive plantation felling by dissatisfied local residents, public criticism from NGOs, and an unfavorable carbon storage review, the investors withdrew and the project discontinued (Eraker, 2000 b). A project, with less contested tenure and more local involvement faired better. Degraded areas of Kibale National forest were replanted, storing 7.2 Tg C and employing local residents in project management, monitoring, and planting (Watson et al., 2000; World Resources Institute, 2002).

It is the job of a host nation's National CDM Authority to define its own **sustainability goals** in a transparent and participatory manner and use these to assess and approve carbon projects (Figueres, 2002). Guidelines for project design and management do exist to help project designers, investors, National CDM Authorities, and other stakeholder groups. The Climate, Community, & Biodiversity Alliance (CCBA) is producing a set of **project design standards** for issuing voluntary CCB certification to land-use based carbon offset projects. These include requirements for:

- measuring and documenting carbon baselines and project scenarios in a conservative manner acknowledging errors
- planning to prevent and monitor leakage

- proving the additionality of project activities and carbon benefits compared to the baseline
- upholding human rights
- working within established laws and land tenure agreements
- producing employment and other net benefits for local communities
- “appropriate and unbiased” community training
- ensuring community involvement and input in project design and management
- ensuring transparency of process and documentation
- producing a thorough project risk assessment
- promoting biodiversity preservation through project activities
- promoting water resource improvements through project activities
  (CCBA, 2004)

While national guidelines and methodologies for land-cover based carbon projects have not yet been decided, the Kenyan government has published its own general project approval criteria. These criteria closely resemble those proposed for CCBA certification, indicating that forestry based projects that pass through NEMA’s approval process should not have trouble applying for CCB certification.
To receive Kenya government approval through NEMA, “*all CDM projects must satisfy the following requirements:*

- *Demonstrate firm and tangible contribution to sustainable development;*
- *Be supportive to and consistent with national development priorities and be pegged to poverty reduction;*
- *The technologies transferred must be locally appropriate and environmentally friendly especially, and demonstrate energy efficiency. Necessary precautions must be in place to avoid dumping of substandard technologies;*
- *Contribute to the enhancement of national institutional and human capacity building.*
- *Activities that generate maximum economic, social and environmental benefits should be accorded highest priority;*
- *Address community needs and priorities through effective public participation in project design, planning and implementation in order to ensure equitable distribution of sustainable development benefits.*
- *Contribute to global efforts to achieve stabilization of greenhouse gas concentrations in the atmosphere;*
- *The CDM financial inflows must be over and above the existing Official Development Assistance (ODA);*
- *Consistent with the objectives of the concurrent environmental conventions, including the Convention on Biological Diversity, the Ramsar Convention on Wetlands, and the Convention to Combat Desertification, Agenda 21, as well as with local and national environmental management laws;”*

(Government of Kenya, 2001)

2. Arabuko-Sokoke Forest (ASF) background

2.1 Physical background and forest types

The Arabuko-Sokoke Forest (3^{o}20' S, 39^{o}50'E) is located in Kenya's Coast Province lying in both Malindi (to the north) and Kilifi (south) Districts. The gazetted ASF area covers roughly 416 km^2, with 382 km^2 of indigenous forest (BirdLife 2003). It is the largest existing fragment of the East African coastal forests that once covered much of the coast from southern Somalia to northern Mozambique (Burgess & Clarke, 2000). ASF supports a variety of forest types on different soil types with varied precipitation regimes and altitudes. These conditions are relevant factors for reforestation, conservation, and carbon storing efforts.

The north eastern side of the forest borders the shores of Mida Creek at sea level. Elevation increases westward, with a steep climb from the eastern costal plain (0-45 m above sea level) to a plateau in the central and western side of the forest (60-135m above sea level) reaching a peak of 210m in the southwest corner. While climatic conditions are thought to have been relatively stable in the last 30 million years due to proximity to the ocean (Axelrod & Raven 1978), there is notable spatial and inter- and intra-annual variation. Average rainfall varies across the elevation gradient with the eastern side closer to the coast receiving 1,000 - 1,100 mm/yr and north-western forest receiving 600 - 900 mm/yr. The yearly rainfall cycle is generally bimodal with long rains occurring April to June and short occurring November to December, however the short rains are often insignificant at the southern end of the forest. The region suffers from extreme dry seasons, droughts, El Nino effects, and floods. A mean daily temperature of 25° C and high humidity remain fairly constant throughout the year.

ASF is generally described as supporting **three major forest types** on the three major soil types occurring there:

- ***Cynometra* forest and thicket**, (23,500 ha) occurring on the western ridge of deep and leached red Magarini soils, composed of dense forest with a range of canopy heights (5-20m) but all dominated by *Cynometra webberi* trees. (Other common species: *Manilkara sulcata*, *Oldfieldia somalensis* and (formerly) *Brachylaena huillensis*)

- ***Brachystegia* woodland/forest** (7,700 ha), occurring on a band of white, infertile sands running through the center of the forest deposited by an old river or by slope erosion from the west, composed of well spaced, large (20 m height), deciduous *Brachystegia spiciformis* trees creating a canopy over a shrub understory. Patches of Brachystegia forest also occur on sandy valley bottoms on the western edge of the forest.

- **Mixed forest** (7,000 ha), occurring on the eastern side of ASF on grey colored Pleistocene lagoonal sands and clays, composed of a variety of tree species forming a tall (15-20m), closed canopy semi-deciduous forest. (Common tree species: *Combretum schumannii*, *Drypetes reticulata*, *Afzelia quanzensis*, *Dialium orientale*, *Hymenaea verrucosa*, *Manilkara sansibarensis,* and *Encephalartos hildebrandii (cycad))*
  (ASFMT, 2002; Birdlife International, 2003)

To estimate total forest carbon stock it is necessary to **quantify the area covered by forest types** with discernibly different biomass densities (Brown, 1997; MacDicken, 1997).

Transitions between the listed soil and forest types are fairly sharp, however there is some blurring at the edges with both *Brachystegia* forest and mixed forest occurring on red soil and evidence of possible encroachment of *Cynometra* into *Brachystegia* forest areas (ASFMT, 2002). Other vegetation types found within the ASF boundaries include a few exotic tree plantations and grass and shrub lands surrounding seasonal pools and saline areas.

Previous studies have proposed further differentiation within the above listed classifications and various maps and area estimates of these types (**Table 2**). In 2000 Bilal Butt created GIS for the ASFMT using 1992 aerial photographs and satellite image analysis to create map layers of the three above listed forest types, the plantations, and areas of "other vegetation" (maps in ASFMT, 2002). However, in their 1984 report, Kelsey and Langton used aerial photographs and ground-truthing to produce a more differentiated map, subsequently refined by Roberston and Luke, in which the **Cynometra forest/thicket** was split into:

- **Cynometra-Manilkara-Brachylaena forest** occuring on red soils both in the northeast and the southwestern areas of ASF, dominated by the three listed species creating a closed canopy at roughly 10-15m with a thick understory

- **Cynometra thicket** occuring on red soils in the northwest of the forest, comprised of dense shrubs, saplings, and small trees mostly 3-6m tall with few individual trees (typically *Brachylaena hullensis)* reaching 10m (Common: *Cynometra webberi*, *Manilkara sulcata*, *Strychnos drysophylla*, *Brachylaena huillensis*)

- **White sand Cynometra-Afzelia forest** occurring on white sandy soils in the center of the forest, composed of species found in both Cynometra and mixed forest, but more structurally similar to Cynometra thicket.

and **mixed forest** was differentiated into:

- **Afzelia forest/drier mixed forest** occuring on grey soils on the southeastern edge and on the eastern edge just south of Mida Creek, composed of a mixture of tall canopy trees of which *Afzelia quansensis* is/was a dominant

- **Northern mixed forest** (falsely called lowland "rainforest") occuring on grey soils on the northeastern edge near Mida Creek, receiving the most precipitation of all the habitats, composed of mixed tall canopy species with a tightly closed canopy and dense understory (Kelsey & Langton, 1984, Robertson & Luke, 1993).

The report also included a rough map of primary and secondary forest areas based on their assessment of sawmill logging damage as seen in aerial photographs. These maps were scanned and digitized for this study. A third category of Cynometra forest has been described as "**impenetrable Cynometra thicket**" with dense vegetation that has a low 5 m canopy occurring in the dry north-western part of the reserve. Both the white sand Cynometra and this impenetrable thicket were classified as "other vegetation" in the ASFMT map (ASFMT, 2002).

Table 2 Areas of land cover types identified in Arabuko-Sokoke Forest

Areas as reported by Kelsey & Langton (1984) and ASFMT (2002) and calculated using GIS layers created by B.Butt for ASFMP and J.Glenday for this study. Some polygons classified as 'other vegetation' in the ASFMP GIS were classified as Cynometra based on ground-truthing.

Differences in areas may represent changes in cover or different means of classification. In the case of the 'Plantation' class, the classification methods used in by J.Glenday in this study only classified fully grown plantations (closed canopy, tall trees) as 'plantation' while younger plantations would go into the 'other' class.

Cover class	Estimated area (ha)				
	Kelsey & Langton, 1984 (aerial photo, 1983)	**KIFCON, 1992** (aerial photo 1992)	**Bilal Butt, 2002** (aerial photo 1992, satellite 1992)	**ASFMT, 2002**	**J. Glenday, 2005** (satellite 2003)
Brachystegia forest	6,700	7,700	7,740	7,700	7,710
Cynometra forest/thicket	25,300	23,600	23,530	21,200	23,490
Cynometra forest	12,200			9,900	12,160
Cynometra thicket	13,100			11,300	11,330
mixed forest	5,200	6,300	7,250	6,300	7,140
other thicket'/'impenetrable thicket'/'undifferentiated scrub'		3,000	1,970	2,300	2,130
Plantations		600	560	700	400
Other (bare, grassland, shrubland, open woodland)		500	620	3,400	830
FORESTED AREA	37,200	40,600	40,490	37,500	40,470
TOTAL AREA		41,700	41,670	41,600	41,700

2.2 Management

Government management of ASF, initiated by the British colonial government, fostered harvesting regimes that depleted the forest's carbon stock, but government and NGO effort to preserve and promote forest regeneration have grown in recent decades. ASF was once sparsely inhabited by Sanya hunter-gatherer groups, but in the 1920's European timber merchants began businesses there attracting other people to the area. About 39,100 ha of ASF was proclaimed a Crown Forest in 1932 and then a **Forest Reserve** in 1943, allowing the British colonial government manage the forest's fate and its profits. The Kararacha extension, 2,676 ha on the eastern side of ASF, was added in 1968, while surrounding areas were being allocated to farmers in a settlement scheme. The Mahaji settlement of 200 ha was degazetted in the scheme as the area had already been cleared and farmed.

Until 1991, ASF was managed by the **Forest Department (FD)** and government revenue production from forest produce was one of its management goals. **Sawmillers** purchased FD licenses to fell the valuable indigenous hardwoods (eg. *Manilkara sansibarensis, Afzelia quanensis, Brachylaena huillensis*). Sawmill camps existed within ASF at Dida, Kararacha, Mida, Arabuko, and Jilore, but by the 60's and 70's the major sawmills were closing. Most sizeable trees of commercial species had been cut without replanting, so it was economically infeasible to continue operations. Despite the over-harvest, logging licenses continued to be granted. This harvesting regime undoubtedly reduced the forest carbon stock.

By 1968, with growing settlements around ASF and little saleable timber left inside, a central area of 2,700 ha containing all three major forest types was declared a **Nature Reserve** in which extractive uses were prohibited. The area was to allow research on forest growth to inform management plans. In 1979, the area was extended to 4,335 ha. Timber harvesting was legal outside the Nature Reserve until a 1982 presidential ban. Selective logging continued *illegally* even within the Nature Reserve (Kelsey & Langton, 1984). Collection of deadwood for *domestic use* remained legal on a head-load permit system. *Commercial* fuelwood collection licenses could be bought through the FD until a 1999 ban on all extractive use of indigenous forest (Wright, 1999). If abided by, it can be supposed that restrictions on extractive use have allowed some regrowth and carbon sequestration in ASF

Unfortunately, enforcement of forest-use prohibitions by forest guard patrols hasn't prevented continuing illegal logging activity (Kelsey & Langton, 1984; Wright, 1999; author's observations, 2004). There are 3 forest stations (Gede, Jilore, Sokoke) plus guard outposts at forest borders in most surrounding sub-locations. Even with guards stationed at all outposts to do daily foot patrols, it was noted in several reports that patrolling guards were rarely observed and high levels of illegal timber extraction continued relatively uninhibited (Kelsey & Langton, 1984; Wright, 1999). Several outposts were abandoned at the time of this study and FD/KWS patrol reports indicated that recent patrols were performed by guard groups in vehicles from the Gede Forest Station, visiting a single location on a day.

In 1991, the **ASF Management Team (ASFMT)** was formed through a memorandum of understanding (MoU) between the **Forest Department (FD)** and the **Kenya Wildlife Service (KWS)**, later joined by **Kenya Forestry Research Institute (KEFRI)** and **National Museums of Kenya (NMK)**. The ASFMT is housed at the Gede Forest Station. The members of the ASFMT coordinate activities through work groups on forest management, rural development, tourism and education, and research and monitoring as overseen by a Senior Management Committee (SMC).

The ASFMT has received assistance from sundry NGOs to create its management plan. Kenya Indigenous Forest Conservation Project (KIFCON), performed biodiversity, socioeconomic, and management reviews from 1990-1992 suggesting frameworks for cooperative management, forest zonation, and community involvement. Starting in 1996, BirdLife International initiated the **ASF Management and Conservation Project (ASFMCP)** with ASFMT, to promote sustainable management practices with community involvement. BirdLife's local partner, **Nature Kenya**, has been engaged in forest management, community participation, research, and planning. The European Union funded this through 2001 and funded the *Arabuko Sokoke Management Plan from 2002-2007,* with the goal of achieving 'a fully functional ecosystem with no change in forest area by 2027 through sustainable management' (ASFMT, 2002).

This management plan includes **zonation** of ASF and its buffer zone into:

- **non-extractive zone** lying in the center of the forest with a *biodiversity conservation sub-zone* and *eco-tourism sub-zone*;
- **subsistence zone** lying just inside the forest boundary with a *community use subzone* for pole and fuelwood harvesting up to 1 km from the eastern forest border and 2 km from the western border and *non-timber forest products sub-zone* for medicinal plant and beekeeping activities extending 1 km further into the forest*;*
- **commercial zone** consisting of the current plantation areas within ASF
- **intervention zone** consisting of the private land of the forest adjacent dwellers (FADs),

who are to receive support in alternative income projects that promote forest conservation (ASFMT, 2002)

Local communities have formally interacted with the ASFMT by means of the **Forest Adjacent Dwellers Association (FADA)** created in 1999. Plans have been made to enhance direct involvement through **Participatory Forest Management (PFM)** of 'subsistence zones' by FAD communities. A government approved pilot PFM project was initiated in the **Dida location** on the southwest border of the forest. Participatory forest resource appraisals and use-zoning of a 14 km long and 3 km deep strip inside the forest border have been performed by members of the **Dida Forest Adjacent Area Forest Association (DIFAAFA)** and Nature Kenya. Their results were being used to devise a **sustainable harvest plan** for fuelwood, polewood, and medicinal plants from this strip. With government and ASFMT approval, the Dida community will be responsible for the plan's implementation.

Over the various stages of management and plan development, a number of forest inventories, biodiversity surveys, and disturbance assessments have been performed by various organizations such as: KIFCON (Davies, 1993; Blackett, 1994), BirdLife (Kelsey & Langton, 1984; Fanshaw, 1995), Oxford Forestry Institute (Wright, 1999), KEFRI (Wairungu et. al 1993 with Robertson & Luke, 1993, Muchiri et al, 2001), and DIFAAFA with the ASFMT (Mbuvi et al. 2004) using a variety of methodologies. A system of regular sampling of **Permanent Sample Plots (PSP)** throughout the forest with a unified methodology is still being initialized. While KEFRI has semi-permanently marked plots with corner trenches and notched trees throughout ASF, these plots are of different sizes and shapes inside and outside the Nature Reserve area and have been sampled with different methodologies at different times (Wairungu et al, 1993; Muchiri et al., 2001, *Appendix A*).

2.3 Forest use, land use, & land cover change

While there has been little change of land cover within the gazetted ASF area, there has been **large-scale clearance of dry coastal forest outside ASF** and **continual human disturbance within**. People haven't been permitted to live inside the ASF area, with the past exception of sawmill camps, but populations around ASF have grown rapidly. Recent reports recorded 54 villages surrounding the forest supporting 104,000 people (ASFMT, 2002). The FAD population was generally found to be subsistence farmers of the Giriama ethnic group, who have farmed west of ASF for over 100 years and settled the east in the 1950s and 60s.

Land was cleared for smallholder agriculture for growing villages around ASF as people immigrated to work at the sawmills or were located there in settlement schemes. Aerial photographs from the 1960's showed a cohesive forest block extending much further south than ASF's gazetted area, but roughly 50% of the forest was cleared by the 1980's leaving little forest outside ASF (Kelsey & Langton, 1984). Kelsey and Langton estimated that 37,200 ha within ASF had indigenous forest cover in 1983, a 2,800 ha (7%) loss since 1979 surveys (Kelsey and Langton, 1984). More recent reports estimated 'forest cover' at 38,200 ha (Wright, 1999; BirdLife, 2003; ASFMT, 2002) and up to 40,490 (calculated from Butt map, ASFMT 2002), either indicating regeneration or differences in forest detection.

Several coastal **forest patches** near ASF that survived settlement clearances have remained as **trustland,** managed by local county councils. Except for some sacred Kaya forests, many have been overexploited and/or partially cleared for cultivation (Robertson & Luke, 1993; Ngala, 2004). A survey of trustland in Marafa division, north of ASF, found Cynometra thicket/forest and Brachystegia forest areas were logged for charcoal, fuelwood, timber, and carving wood or cleared for agriculture (Ngala, 2004). **Madunguni Forest,** (approximately 860 ha) was a county council forest on the north end of ASF. In the early 1990s, plots in Madunguni were **cleared for cultivation** with local political encouragement. Little closed forest remained there at the time of study (*see section 4.6.b*) and a large erosion scarp, thought to be migrating south towards a main road and water pipe, means high risk for continued erosion. In November 2004, the area was gazetted for FD management. Potential plans to relocate its inhabitants existed but had not been finalized (FD personal comm.).

Inside the **gazetted ASF area,** there have been **relatively few incidences of complete forest clearance,** none of which have encompassed more than a few tens of hectares. These include a silica mine abandoned in 1988, sawmill yards abandoned in the 1960's and 1970's, and the eastern forest edge damaged in moving the Malindi-Kilifi road, much of which became a eucalyptus plantation (Robertson 1993). In 1994, activists in Kilifi district lobbied for an 8,000 ha excision from ASF for agricultural use, despite its infertile sandy soils (Roberston et al, 1993). Local politicians and community groups around Kararacha continued to request degazettement for settlement into the late 1990's. This increased illegal tree cutting there and incited some forest clearance around Mida by groups hoping forest in their area would also be degazetted. However in 1997, after both local and national level protest against the degazettement, the President stated that no degazettement of ASF would occur.

Although little full clearance has occurred, ASF has been subject to heavy anthropogenic use. In the sawmilling period many, if not the majority of, **large trees of commercial species were cut**. The effects of this on species and size composition in ASF were still evident at the time of study, implying depressed forest carbon densities. Old tree stumps throughout the forest had larger diameters than living trees (Davis, 1993; Robertson & Luke, 1993; Wright, 1999; personal observation, 2004). *Brachyleana huellensis*, once dominant in Cynometra forest and common in mixed forest, and *Afzelia quansensis*, once dominant in mixed forest, became relatively rare and no longer found in large sizes (Kelsey & Langton, 1984; Davis, 1993; Robertson & Luke, 1993; Wright, 1999). The1990s KIFCON surveys found few *B. hullensis* in smaller (5-10 cm dbh) compared to larger sizes, indicating poor regeneration from low recruitment and/or polewood poaching (Blackett, 1994).

The **major threats** to ASF at the time of this study were listed as deforestation or selective logging for commercial wood products as well as fuel and polewood collection for domestic use by growing FAD populations (BirdLife, 2003). Surveys found 60-90% of FAD households relied on the forest for domestic energy needs, with more use on the eastern side where population densities are higher and farm-waste fuel may be less accessible (ASFMT, 2002). Indications of **unsustainable fuelwood harvesting levels** included an observed shift in species used for fuel due to declining availability of preferred species and an increase in travel distance people to obtain resources from 1 km in 1991 to over 2 km in 2000 (ASFMT, 2002). However, some 2001 FAD interviews indicated that farm waste from mango, cashew, and coconut and wood from trustlands was ample to supply cooking fuel needs.

As coastal tourism and urban centers developed near ASF in past decades, demand for timber for construction, furniture, and woodcarvings increased (Robertson & Luke,1993; Wright, 1999; ASFMT, 2002). Due to observed low densities and regeneration of preferred species, **continued commercial timber and carving wood extraction was deemed unsustainable** (Wright, 1999; ASFMT, 2002). Nevertheless harvest rates haven' t shown signs of slowing. Between surveys in 1990 and 1999 *B.hullensis* removal increased (Wright, 1999). Polewood cutting was also thought to be rising, even after a 1999 ban on polewood licenses (ASFMT, 2002). Lacking larger mature trees, young trees were being increasingly harvested for polewood before reaching seed producing age (Wright, 1999; ASFMT, 2002). Such threats to regeneration don't bode well for recovering carbon stock. Accurate levels of **illegal logging** were difficult to estimate at the time of study. Much had gone undetected and, although systematized patrol reporting was given highest priority in 2002 (ASFMT, 2002), patrol reports observed often did not include tree species, sizes, or number removed when illegal logging was reported. In addition, lying in both Malindi and Kilifi, ASF has two separate District Forest Officers and reports from the two sides were not compiled.

3. Methodology

3.1 Inventory plots

Carbon density in ASF was estimated with data from ninety-seven circular, 20m-radius (0.126 ha) inventory plots sampled in November-December 2004. In each plot, six major **carbon storage pools** were assessed (Brown, 1997; MacDicken 1997):

- live tree aboveground biomass,
- tree belowground biomass,
- coarse deadwood (≥10 cm diameter),
- litter,
- herbaceous vegetation,
- soil

Plots were categorized by basic forest type, **Cynometra forest/thicket**, **Brachystegia forest**, and **mixed forest**, and randomly placed within blocks of each type. The number of plots sampled in each forest type was roughly proportional to the relative area covered by each and the predicted **spatial heterogeneity** (variability between different areas in the forest) of carbon density within each class. Plot positions and observed disturbances, such as timber or fuelwood cutting, were recorded using a GPS unit and **geo-referenced** to ASFCMP land-cover maps (ASFMT, 2002). Plots for which field assessments of forest type did not match map classifications were assigned to the cover class seen on the ground if the forest structure clearly from others in the mapped class. Plots located in known areas cleared in the 1930s to 1960s and subsequently abandoned, were classed as **regenerating**. Attempts were made to further classify plots within broad forest types on the basis of canopy height, size distribution, and species composition to determine if sub-classes, such as Cynometra forest vs. thicket, had **significant differences in carbon densities**. Reclassifying mixed forest plots into dry, wet, and white sand, as in previous studies (Kelsey & Langton, 1984; Robertson & Luke, 1993) did not significantly improve separability and was not included in results.

a. Vegetative biomass carbon

Carbon densities (Mg C /ha) in each plot were calculated from **biomass densities,** assuming 50% of vegetative biomass is carbon (MacDickon 1997). To quantify aboveground biomass, tree and liana diameters were recorded at 1.3 m from the ground (**diameter at breast height or dbh**), in ninety-seven inventory plots using a nested sampling design:

- Within a 4 m radius of the plot center, all trees with dbh ≥5cm were measured
- Within a 14 m radius of the plot center, all trees with dbh ≥20cm were measured
- Within a 20 m radius of the plot center, all trees with dbh ≥40cm were measured

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

$$\textbf{\textit{Importance value}}_x = \frac{\textit{relative density}_x + \textit{relative frequency}_x + \textit{relative coverage}_x}{3}$$

- ***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*
- ***relative coverage$_x$*** *= % sampled area covered by species x basal area / sum of all % coverages*

Aboveground biomass (AGB) of each tree was calculated based on diameter using a generalized tropical dry forest equation recommended for rainfall > 900 mm/year (Brown,1997).:

$$\mathbf{AGB}\ (\text{kg}) = e^{\{-1.996+2.32*\ln(\mathbf{dbh}\ \text{cm})\}}$$

Belowground tree biomass (BGB) was calculated for each tree using a regression equation relating aboveground biomass density (AGB) to **root biomass density (RBD)** derived for tropical trees (Cairns et al.,1997):

$$\mathbf{RBD}\ (\text{Mg/ha}) = e^{\{-1.0587+0.8836*\ln(\mathbf{AGB}\ \text{Mg/ha})\}}$$

Coarse deadwood biomass was estimated in each plot using the transect method described by Harmon & Sexton, 1996. Diameters were recorded for all downed trees and branches with diameters≥10 cm crossing two perpendicular 40m transects (the north-south and east-west diameters of the inventory plot). Each piece measured was given a decomposition ranking: rotten, intermediate, or sound. The biomass density of deadwood was calculated using tropical dry forest deadwood densities for the three decomposition classes reported by Jaramillo, VJ et al., 2003. **Standing dead trees** were measured with the live trees, but given decomposition rankings with which to scale down biomass.

Clip plots were used to measure **understory vegetation** and **litter** (MacDicken, 1997). Four 0.5 x 0.5 m subplots were established 10 m from the plot center in each cardinal direction. 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 80-200g sub-sample was weighed, air dried for at least 3 weeks, and reweighed. The wet to dry weight ratio of the sub-sample was used to estimate total dry weight for herbaceous vegetation. This same procedure was followed for litter collected in each clip plot after herbaceous vegetation removal.

b. Soil carbon

Three soil samples were collected per plot from the bare ground revealed after clearing vegetation and litter from the clip-plots. 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, passed through a 2mm sieve, and subsequently weighed. Bulk density was calculated using the measured weight of each dried, sieved sample divided by the core volume. Soil cores in which considerable compaction was observed were not included.

Sample carbon concentrations were predicted using the spectral library approach described by Shepherd and Walsh, 2002. All samples were analyzed 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. Soil carbon was measured on a random selection of 15% of the samples by acid oxidation. Measured concentrations for this subset were used to calibrated the 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 (*Appendix B*). The average carbon concentration at each depth was found for each sampled strata and multiplied by the bulk density to estimate soil carbon density (Mg C/ ha).

c. Stump measurements: recent disturbance & historical forest structure

In each inventory plot, stump species and diameters were measured using the same nested subplot design described above (*section 3.1.a*). Stumps appearing to have been cut within the past six months were classified as 'fresh' by visual assessments (wet wood, lack of decay or insect damage on cut surface, green leaves on cut branches, etc). For commonly felled species, both **diameters at ground level (dgl)** and dbh measurements were taken on living trees. The dgl/dbh ratio was applied to stump dgls to estimate former dbh and calculate former biomass. Estimated biomass removal was used to assess disturbance levels.

3.2 Landscape scale assessment

Mapping forest cover types

The area covered by each forest type was determined using cover maps derived from aerial photographs in previous studies and post-hoc spectral analysis of Landsat satellite images (*scene*: 166/62, *images*: 24/6/1992 from Landsat TM, 29/9/2004 from L7 ETM). Images were selected based on lack of cloud cover. Spectral analyses were performed using the "maximum likelihood function" in ENVI 4.1 (copyright Research Systems, Inc., USA) remote sensing software. Locations with vegetative cover that clearly fit into established forest type descriptions were GPSed in the field and used as 'training classes' in the satellite images. The separability of the average spectra for the training class areas for the cover types was estimated using Jeffries-Matusita separability index (calculated by ENVI 41.) and classes with values lower than 1.95 were either lumped or new training area pixels chosen.

Image pixels were assigned to land cover classes based upon their spectral similarity to the average spectra of training class areas. Small areas that could not be assigned to a ground cover class due to cloud interference in one image were assigned based on their classification in the other image. The accuracy of the classification was determined by comparing the resulting classification with field classification of GPSed points not included in the training set. The resulting map of land cover was compared with previous maps of the area and used to estimate areas of each forest cover type and identify land cover changes.

a. Land cover change assessment & Madunguni Forest

Land cover maps from previous studies (Kelsey & Langton, 1984, Robertson et al. 1993, ASMT, 2002) were digitized and compiled into a GIS for comparison with those produced from Landsat imagery in this study. Forest cover changes were assessed within ASF and Madunguni by overlaying the maps using the 'union' function in ArcView 3.2 (copyright Environmental Systems Research Institute, Inc., USA).

b. Scaling up to forest level: aggregation & extrapolation

Individual **plot carbon density** was calculated as the sum of the carbon densities found in all six measured carbon pools. The **average carbon density for a forest type** was calculated by taking the mean of all plot carbon densities in that type. Total ASF carbon stock was estimated by multiplying average carbon density estimates by the estimated area covered for each different forest type.

c. Spatial patterns of carbon storage, disturbance, & cofactors

Geo-referenced locations of towns, roads, major forest trails, forest stations, guard posts, and historical sawmills, GPSed in the field or included in the ASFCMP land cover GIS were used to look for significant trends in carbon storage values or the occurrence of disturbances with distance from a potential cofactor. Factors, such as accessibility for 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 forest type was random, as opposed to distributing plots with the aim of assessing changes over a specific distance gradient, these comparisons are merely exploratory and lack of statistical significance is not conclusive.*

3.3 Statistics & Uncertainty

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 standard student's t-tests, except in cases where data was found to be significantly non-normal in distribution. In these cases Tukey's HSD test was used for pair-wise comparisons.

Both *measurement uncertainties* in measuring plot radius and tree diameter and the *applicability of the regression equation* used to the growth forms of the forest sampled contribute to the uncertainty in carbon density estimates. However, it has been repeatedly found that measurement uncertainties contribute an insignificant amount to overall **uncertainty in the mean** compared to uncertainty introduced by natural variations of carbon density between individual plots of one forest type (Chave et al. 2003, Keller et al 2001, Brown et al. 1995). Without destructive tree sampling, non-viable in a protected reserve, the applicability of the generalized dry forest equation used cannot be assessed. For these reasons only *sampling error*, rather than sampling, measurement, and equation errors, was included in the **95% confidence interval (95% CI)** estimates presented for all mean values. A **sensitivity analysis** was used to assess the influence of various definitions of forest cover types and various estimates of forest type areas on the total carbon stock estimate.

4. Results

4.1 Forest structure

To increase precision, an effort was made to divide general forest types into subclasses with distinct carbon densities. Previous studies noted wide variations of canopy height and dbh distribution in Cynometra and Mixed forest areas (Kelsey & Langton, 1984; Robertson & Luke 1993). Plots were therefore **separated into 'thicket' and 'forest'** subclasses, a split deemed useful as it produced subclasses with significantly different mean carbon densities. Plots with canopy heights ≤10 m, having more than 90% of trees with dbhs ≤20 cm, or found in areas identified as 'thicket' in previous studies (Kelsey & Langton, 1984; 'other vegetation' in ASFMT, 2004) were considered for '**cynometra thicket**' or '**mixed thicket**' classes. Plots satisfying all criteria were classified as 'thicket.' Plots satisfying two criteria were classified based on size distributions. Plots located in the northwestern area identified as "impenetrable thicket" or "other vegetation" (ASFMT, 2004), were found to have thicket characteristics, but a different species composition to both Cynometra and mixed thicket and therefore classed as '**other thicket'.** Structural differences are illustrated in *Figure 1.*

Figure 1

Table 3 Importance values for the top 10 species dominating sampled areas of the different forest types in Arabuko Sokoke Forest, 2004

Importance values calculated from relative frequency, relative stem density, and relative basal area as described in methods 3.1.a

Brachystegia Forest		Cynometra Forest/Thicket		Mixed Forest		Other thicket	
Species	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**
Brachystegia spiciformis	39.2%	*Cynometra webberi*	45.8%	*Manilkara sanzibarensis*	15.0%	*Brachyleana hulliensis*	30.3%
Manilkara sanzibarensis	14.2%	*Manilkara sulcata*	14.5%	*Combretum schumannii*	10.5%	*Manilkara sulcata*	29.6%
Strychnos madagascariensis	7.2%	*Memecylon sansibaricum*	4.6%	*Hymenea verrucosa*	9.0%	*Strychnos madagascariensis*	27.4%
Lepisanthes senegalensis	5.9%	*Strychnos madagascariensis*	2.9%	*Afzelia quanzensis*	5.2%	*Oldfieldia somalensis*	12.7%
Julbernardia magnistipulata	5.8%	*Aristogeitonia monophylla*	2.8%	*Elliphanthus hemandranioides*	4.8%		
Ozoroa obvata	3.5%	*Croton pseudopulonellus*	2.3%	*Julbernardia magnistipulata*	4.7%		
Hymenea verrucosa	3.3%	*Diospyros consolatae*	1.7%	*Grewia plagiophylla*	4.7%		
Ludia mauritiana	3.3%	*Ozoroa obvata*	1.5%	*Ozoroa obvata*	4.4%		
Boscia angustifolia	3.2%	*Cynometra suhalensis*	1.3%	*Drypetes reticulata*	3.1%		
Afzelia quanzensis	2.5%	*Psydrax faulknerae*	1.1%	*Manilkara sulcata*	2.9%		

The dominant species seen in the broad forest types were consistent with previous descriptions (Kelsey & Langton, 1984; Robertson & Luke, 1993, Birdlife, 2003). **Brachystegia forest** was dominated by *Brachystegia spiciformis* with significant contributions from *Manilkara sulcata.* **Cynometra** was dominated by *Cynometra webberi* with significant contributions from *M. sulcata.* **Mixed forest** was dominated by *Manilkara sansibariensis* with significant contributions from *Hymenea verrucosa*, *Afzelia quanzensis*, and *Combretum schumannii* (*Table 3*). However, the "**other thicket**" area, sometimes mapped as Cynometra thicket (Kelsey & Langton, 1984; Robertson & Luke, 1993) actually had no *Cynometra webberi* and was dominated by *Brachylaena hullensis* and *M. sulcata* with significant contributions from *Strychnos madagascariensis* and *Oldfeldia somaliensis*.

Different structure subclasses within the Cynometra and mixed classifications had different species compositions (*Table 4*). Both Cynometra forest and thicket were dominated by *C. webberi* with significant contributions from *Manilkara sulcata*, but **Cynometra thicket** had a more mixed species distribution (more even spread of dominance values) and a greater contribution from *Brachylaena hullensis* compared to **Cynometra forest**. The sampled **mixed thicket** area was generally dominated by trees of small stature, such as *Combretum schumannii* and *Grewia plagiophylla* with significant contribution from *M. sulcata*. These species were also among the top ten species in the **tall mixed forest**, but the 'forest' class was largely dominated by taller tree species: *Manilkara sanzibarensis*, *Hymenea verrucosa*, and *Afzelia quanzensis.* These taller species are among those favored for timber and heavily logged by sawmills. This may indicate that the mixed thicket may be a result of anthropogenic disturbance. Indeed, as detailed below, a higher frequency and intensity of disturbance was seen in mixed thicket than in mixed forest (*Table 8*)

Table 4 Importance values for the top 10 species dominating sampled areas of the various Cynometra and Mixed forest classes in Arabuko Sokoke Forest, 2004

Cynometra Forest/thicket		Cynometra Forest		Cynometra Thicket		Cynometra Regenerating	
Species	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**
Cynometra webberi	45.8%	*Cynometra webberi*	48.8%	*Cynometra webberi*	43.6%	*Azadirachta indica*	40.9%
Manilkara sulcata	14.5%	*Manilkara sulcata*	14.2%	*Manilkara sulcata*	14.9%	*Diospyros consolatae*	23.1%
Memecylon sansibaricum	4.6%	*Aristogeitonia monophylla*	5.6%	*Memecylon sansibaricum*	6.6%	*Cynometra webberi*	21.2%
Strychnos madagascariensis	2.9%	*Memecylon sansibaricum*	3.1%	*Strychnos madagascariensis*	5.3%	*Newtonia paucijuga*	14.8%
Aristogeitonia monophylla	2.8%	*Croton pseudopulonellus*	2.8%	*Brachyleana hulliensis*	4.0%		
Croton pseudopulonellus	2.3%	*Haplocoelum inoploeum*	2.8%	*Ozoroa obvata*	3.3%		
Diospyros consolatae	1.7%	*Cynometra suhalensis*	2.4%	*Diospyros consolatae*	2.6%		
Ozoroa obvata	1.5%	*Strychnos xylophylla Gilg*	1.5%	*Manilkara sanzibarensis*	2.3%		
Cynometra suhalensis	1.3%	*Oldfieldia somalensis*	1.4%	*Pluchea dioscoridis*	2.2%		
Psydrax faulknerae	1.1%	*Elliphanthus hemandranioides*	1.4%	*Ochna thomasinana*	1.9%		

All Mixed Forest		Mixed Forest - tall		Mixed Thicket		Mixed Regenerating	
Species	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**	***Species***	**Importance Value**
Manilkara sanzibarensis	15.0%	*Manilkara sanzibarensis*	22.1%	*Combretum schumannii*	14.7%	*Julbernardia magnistipulata*	33.2%
Combretum schumannii	10.5%	*Hymenea verrucosa*	12.8%	*Grewia plagiophylla*	12.8%	*Manilkara sanzibarensis*	15.5%
Hymenea verrucosa	9.0%	*Afzelia quanzensis*	12.5%	*Ozoroa obvata*	9.4%	*Afzelia quanzensis*	10.6%
Afzelia quanzensis	5.2%	*Combretum schumannii*	10.2%	*Elliphanthus hemandranioides*	7.7%	*Hymenea verrucosa*	9.9%
Elliphanthus hemandranioides	4.8%	*Drypetes reticulata*	3.6%	*Manilkara sulcata*	6.1%	*Dialium orientale*	5.9%
Julbernardia magnistipulata	4.7%	*Elliphanthus hemandranioides*	2.7%	*Carpodiptera africana*	4.5%	*Elliphanthus hemandranioides*	3.2%
Grewia plagiophylla	4.7%	*Julbernardia magnistipulata*	2.3%	*Nesogordonia holstii*	4.5%	*Memecylon mourifolia*	2.8%
Ozoroa obvata	4.4%	*Brachyleana hulliensis*	2.3%	*Ludia mauritiana*	4.3%	*Garcinia livingstonei*	2.5%
Drypetes reticulata	3.1%	*Flacourtia indica*	2.1%	*Drypetes reticulata*	3.8%	*Lepisanthes senegalensis*	2.2%
Manilkara sulcata	2.9%	*Ozoroa obvata*	2.0%	*Lepisanthes senegalensis*	3.3%	*Ficus natalensis*	2.1%

Table 5 Comparison of species composition and basal areas in different forest types observed in different inventories of Arabuko Sokoke Forest

Forest type	Number of species observed			Top 3 most frequent species in sample (by stem density)		
	Blackett, 1994	*Muchiri et al., 2001*	*Glenday, 2005*	*Blackett, 1994*	*Muchiri et al., 2001*	*Glenday, 2005*
Brachystegia forest	22	25	19	*Brachystegia spiciformis, Julbernadia magnistipulata, Manilkara sulcata*	*Brachystegia spiciformis, Manilkara sulcata, Julbernadia magnistipulata*	*Brachystegia spiciformis, Manilkara sansibariensis, Strychnos madagascariensis*
Cynometra forest/thicket	48	29	45	*Cynometra webberi, Manilkara sulcata, Vismia orientalis*	*Cynometra webberi, Manilkara sulcata, Vismia orientalis*	*Cynometra webberi, Manilkara sulcata, Memecylon sansibaricum*
Mixed forest	68	46	57	*Manilkara sansibarensis, Hymenaea verrucosa, Combretum schumannii*	*Manilkara sansibarensis, Hymenaea verrucosa, Elliphanthus hemandranioides*	*Manilkara sansibarensis, Combretum schumannii, Elliphanthus hemandranioides*

Forest type	Mean basal area (m^2/ha), trees of dbh ≥ 5 cm		Mean basal area (m^2/ha), trees of dbh ≥ 20 cm	
	Muchiri et al., 2001	*Glenday, 2005*	*Blackett, 1994*	*Glenday, 2005*
Brachystegia forest	17.1	17.4	9.4	12.3
Cynometra forest/thicket	15.9	16.1	5.4	6.3
Mixed forest	17.6	16.4	7.5	8.8

Structural results were generally consistent with previous inventories, with similar species numbers and basal areas (*Table 5*). As this was not a re-sampling of previous plots, differences may result from 'sampling error' (sample plots may not capture all the variation and the true mean for the entire forest). It is also possible that differences reflect growth or changes over time.

The three major forest types generally corresponded with expected **soil types** (*see section 2.1*). Soil variations within forest types, between subclasses, may indicate further ties between finer soil and vegetation classes (*Appendix C*). The majority of Cynometra plots were found on red silts and clays with 4% on sandy soil. Amongst the red soils, darker 'brown/red' soils were generally seen at higher altitudes. More '**Cynometra forest'** plots (56%) were located on these darker soils, compared to '**Cynometra thicket'** plots (26% 'brown/red,' 68% 'red') (*Appendix C*). The majority of all mixed forest plots (93%) occurred on pale brown sandy soils. However, 44% of '**mixed thicket'** plots had red silty soils, while no '**tall mixed forest'** plots had this soil type. The red soil mixed thicket was found in northeastern ASF near the Cynometra areas and may represent a transitional area between forest types.

Where forest remained in **Madunguni,** it had similar characteristics to ASF forest. Madunguni was found to have both **Cynometra forest** and **thicket** growing on red silt and clay soils. The two northernmost plots located at lower elevations down Madunguni's erosion scarps were found to support thicket vegetation whereas the four plots higher up on the flatter plateau were classified as forest. The area was dominated by *Cynometra webberi* and *Manilkara sulcata,* as seen in ASF, but there was a more significant contribution from *Croton pseudopulonellus* than seen in the rest of the forest. (*Appendix D*).

4.2 Mapping forest cover

Spectral analyses of Landsat images (*Figure 2, Tables 2 & 10*) were able to differentiate between the Brachystegia, Cynometra, mixed forest, and 'other thicket' with an accuracy of 95%. Mismatched field and map classifications were found to occur in plots with patches of bare ground classified as shrubland or other thicket. One mismatch occurred at a Brachystegia and mixed forest border. Edge areas do contain a mix of characteristic vegetation for both forest types. Comparing the satellite classification map with those of previous studies, the Brachystegia boundary is slightly different, likely for the same reason.

Accuracy decreased to 75% when mapping thicket and forest subclasses because field based differentiation between thicket and forest did not strongly correspond to spectral differences in the Landsat image analyzed. Cynometra thicket and forest classes showed higher map user's and producer's accuracies (80-87%) than mixed thicket and tall forest (50-67%). It may not be possible to accurately differentiate between field classified mixed thicket and tall forest with Landsat image spectral properties alone or it may be that the inaccuracy is a factor of sampling error in the training classes used or the conditions particular to the image used (season, forest greenness, particulate scattering, etc. in the single image).

4.3 *Carbon densities of ASF forest types*

In all major forest types ***live tree aboveground biomass (AGB)*** made up roughly 50% of the total carbon density, while ***soils*** and ***belowground biomass (BGB)/roots*** made up approximately 20-30% and 15% respectively (*Figure 3, Table 6*). *Litter, standing dead trees,* and *coarse woody debris* (fallen dead wood), collectively made up 8-10% of the total, while herbaceous vegetation contributed under 1%.

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, but carbon densities for ***tree biomass*** and ***soils*** were significantly different across forest types (*Figure 3, Table 6*). **Brachystegia forest,** with large trees on sandy soils, had the *highest tree* carbon (AGB, 46 ± 5; BGB, 12 ± 1 Mg C/ha), significantly higher than Cynometra (AGB, 35 ± 5; BGB, 10 ± 1 Mg C/ha), but the *lowest soil* carbon (13 ± 1 Mg C/ha), significantly lower 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 to 0.07 Mg C/ha), expected due to its open upper canopy. **Cynometra** had the *lowest coarse deadwood* (1.1 ± 0.2, vs. 1.8 to 1.9 Mg C/ha) and *litter* (1.8 ± 0.2, vs. 3.3 to 4.6 Mg C/ha).

Splitting forest types into **forest** and **thicket subclasses** increased separability between carbon densities:

- **Amoung Cynometra plots**, mean *total* carbon density for **forest** (83 ± 8 Mg C/ha) was significantly *greater* than **thicket** (65 ± 6 Mg C/ha) and **regenerating** (35 ± 12 Mg C/ha). Cynometra classes had similar *soil* carbon, but *AGB* carbon density in 'forest' plots was significantly *higher* than thicket by 14 Mg C/ha and regenerating by 33 Mg C/ha.

- **Amoung mixed forest plots**, mean *total* carbon density for **tall mixed forest** (94 ± 16 Mg C/ha) was significantly *greater* than **thicket** (64 ± 11 Mg C/ha) and **regenerating** (51 ± 37 Mg C/ha). 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 had similar *soil* carbon density (22 ± 6 Mg C/ha) to tall mixed forest (23 ± 7 Mg C/ha), but regenerating areas had lower soil carbon than both forest and thicket.

Tall mixed forest had the *highest total carbon density* of all types, significantly higher than Brachystegia forest, all thicket types, and regenerating areas. Brachystegia had significantly *higher total* carbon density than Cynometra thicket, other thicket, and regenerating areas and *higher AGB* carbon than mixed thicket. **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). **Other thicket,** despite having higher soil carbon, had the *lowest total* carbon density (58 ± 3 Mg C/ha) of thicket class due to low AGB.

Regenerating areas had lower carbon densities than mature areas, but, due to small sample sizes from small cleared areas in ASF and high carbon variance between plots, significant differences were not established. Sampled regenerating areas were the old Dida sawmill in Cynometra and the old silica mine and old Kararacha sawmill in mixed forest. Both mixed forest areas sampled had a few large trees that hadn't been cleared, adding AGB, while sand mining would have removed topsoil with carbon stored in organic matter from litterfall, reducing soil carbon at the mine. As expected, **mixed forest regenerating** areas sampled had higher mean *total* carbon density than Cynometra, with *lower soil* carbon by 10 Mg C/ha and greater AGB carbon by 15 Mg C/ha. This could also relate to forest age, prior land use, and/or inherent differences in the growth patterns of these forest types.

Table 6 Mean total carbon densities and carbon pool densities for forest classes in Arabuko-Sokoke Forest, 2004

Carbon densities for various forest type classifications calculated as the mean of the calculated carbon densities for inventory plots. Plots in Madunguni are included. Carbon densities and their percent contribution to the total carbon density are included for the three most significant carbon pools: live tree aboveground biomass (AGB), live tree belowground biomass (BGB) (roots), and soil. *95% confidence intervals (CI) were calculated for each mean.*

**Statistically significant differences between means determined at α≤0.05*

*** Statistically significant differences between means determined at α≤0.1*

Forest class	plots sampled	Mean Carbon Density (Mg C/ha)										
		Total C	95% CI	**live tree AGB**	95% CI	*% of total C*	**live tree BGB**	95% CI	*% of total C*	**soil**	95% CI	*% of total C*
brachystegia forest	22	**80**	6	**46**	5	*58%*	**12**	1	*15%*	**13**	1	*17%*
Significantly different from:*		*cynometra thicket & regenerating, mixed forest tall & regenerating***		*cynometra forest/thicket, cynometra thicket & regenerating, mixed thicket & regenerating, other*						*cynometra forest/thicket, cynometra forest & thicket, mixed forest*		
cynometra forest/thicket	46	**74**	6	**35**	5	*47%*	**10**	1	*13%*	**24**	2	*32%*
Significantly different from:*				*brachystegia forest*			*brachystegia forest*			*brachystegia forest*		
cynometra forest	*25*	***83***	8	***42***	6	*50%*	***12***	2	*14%*	***25***	2	*30%*
cynometra thicket	*18*	***65***	6	***28***	5	*43%*	***8***	1	*12%*	***22***	3	*34%*
cynometra - regenerating	*3*	***35***	12	***9***	5	*25%*	***2***	2	*7%*	***21***	4	*60%*
Significantly different pairs:*		*cynometra forest vs. thicket, cynometra forest vs. regenerating*		*cynometra forest vs. thicket, cynometra forest vs. regenerating*								
mixed forest	27	**78**	6	**38**	8	*49%*	**11**	2	*14%*	**21**	4	*27%*
Significantly different from:*		*cynometra thicket & regenerating*		*cynometra thicket & regenerating*						*brachystegia forest*		
mixed forest tall	*14*	***94***	16	***50***	11	*53%*	***14***	3	*14%*	***23***	7	*25%*
mixed thicket	*9*	***64***	11	***27***	8	*42%*	***7***	2	*12%*	***22***	6	*35%*
mixed - regenerating	*4*	***51***	37	***24***	23	*46%*	***7***	6	*13%*	***11***	2	*22%*
Significantly different pairs:*		*mixed forest tall vs. thicket, mixed forest tall vs. regenerating*		*mixed forest tall vs. mixed thicket*						*mixed forest tall vs. mixed regenerating*		
other thicket	2	**58**	3	**23**	7	*39%*	**7**	2	*12%*	**24**	3	*41%*
Significantly different from:*		*brachystegia forest, mixed forest tall, cynometra forest*		*brachystegia forest, mixed forest, cynometra forest*								

Table 7 Mean total and pool carbon densities found in other studies of dry and African forests (See references for full citations of sources),
AGB - aboveground biomass, BGB – belowground biomass or roots, most studies only include woody vegetation with dbh > 5cm

The GIS model created by Brown & Gaston predicted potential AGB carbon from precipitation data, climactic indices, elevation, slope, and soil texture. Actual AGB was predicted based on degradation ratios from potential AGB relating to population density. In both cases models were calibrated with field data.

Continent	Country	Moisture class	description	Mean carbon density (Mg C/ ha)							Source	
				total	AGB	% of total	BGB	% of total	soil	% of total		
Africa	Kenya	country mean	Actual AGB estimated from GIS model		16	CV = 0.8					Brown & Gaston	1995
Africa	Kenya	country mean	Potential AGB estimated from GIS model		29	CV = 1.04					Brown & Gaston	1995
Africa	all tropical	dry	Actual AGB estimated from GIS model		30	CV = 1.12					Brown & Gaston	1995
Africa	all tropical	dry	Potential AGB estimated from GIS model		46	CV = 0.96					Brown & Gaston	1995
Africa	South Africa	dry	broadleaf savanna	94	13	14%	2	2%	72	76%	Woomer	1993
Africa	Zimbabwe	dry	miombo woodland (Brachystegia)	48	19	40%	4	9%	21	43%	Woomer	1993
Asia	India	dry	disturbed hilly area		14						Vyas et al.	1977
Asia	Thailand	dry			48						Ogawa et al.	1965
Central America	Belize	dry	secondary forest (40-50 year old)		39						Lambert et al.	1980
Central America	Puerto Rico	dry			22						Murphy & Lugo	1986
Central America	Venezuela	dry		344	70	20%	33	10%	233	68%	Delaney et al.	1997
North America	Mexico	dry	deciduous, leguminous	139	35	25%	7	5%	76	55%	Jaramillo et al.	2003
North America	Mexico	dry	deciduous, leguminous		41						Martinez-Yrizar et al.	1992
Africa	all tropical	seasonal	Actual AGB estimated from GIS model		70	CV = 0.71					Brown & Gaston	1995
Africa	all tropical	seasonal	Potential AGB estimated from GIS model		105	CV = 0.60					Brown & Gaston	1995
Africa	all tropical	moist	Actual AGB estimated from GIS model		189	CV = 0.22					Brown & Gaston	1995
Africa	all tropical	moist	Potential AGB estimated from GIS model		206	CV = 0.15					Brown & Gaston	1995

ASF carbon densities found generally fit into the range of values in published field studies and models of dry tropical forests (*Table 7*) and were consistent with previous studies in ASF (*Appendix A*). AGB carbon estimates in ASF mature forest classes (23-50 Mg C/ha) were close to values predicted by Brown & Gaston's model for **actual** (30 Mg C/ha) and **potential** (46 Mg C/ha) **AGB carbon densities in African dry forests**. AGB carbon values for the broad forest types in this study were found to be statistically similar to those calculated from data in other recent inventories in ASF: Muchiri et al. (2001) and Wairungu et al. (unpublished data, 2003) (*Appendix A*). Like ASF Brachystegia forest, Zimbabwean **miombo woodland** is also dominated by large, well spaced *Brachystegia spiciformis* trees. However, its observed AGB carbon (19 Mg C/ha; Woomer, 1993) was less than half that of ASF Brachystegia forest (46 ± 5 Mg C/ha). This could reflect higher densities of other forest species and shrubs in ASF Brachystegia *forest* over what is commonly considered *woodland*.

Soil carbon densities in ASF forest types (22-25 Mg C/ha) were 45-110 Mg C/ha *lower* than estimated soil carbon density in South African savanna and Venezuelan and Mexican dry forests (Woomer, 1993; Delaney et al.,1997; Jaramillo et al., 2003), perhaps due to differences in soil type and/or sampling methodology. Delaney et al. estimated soil carbon to a depth 1 m, while this study only included the top 30 cm. However, ASF soil estimates for all forest types were consistent with Zimbabwean miombo woodland soils (21 Mg C/ha, Woomer, 1993). Comparing the carbon pool contributions to total carbon to published estimates for tropical forests (Brown et al., 1997), ASF **fine litter** percentages were *higher* (up to10% of AGB density vs. 5%) and **coarse woody debris** lower (below 5% of AGB) than expected. Sampling ASF, a semi-deciduous forest, before the rains may explain extra litter. Timber harvesting and fuelwood collection could be related to low deadwood.

4.4 Frequency and distribution of anthropogenic disturbance

Felling of *medium to large trees* (dbh ≥ 20 cm) had been, and still is, widespread throughout the forest. **Old stumps** were seen in the vicinity of 100% of Cynometra plots, 78% of mixed forest plots, and 41% of Brachystegia plots (*Table 8*). Results also show illegal logging is ongoing: **fresh stumps** were seen in the vicinity of 33% of Cynometra plots, 48% of mixed forest plots, and 5% of Brachystegia plots. **Mixed thicket** and **Cynometra forest** had the *highest frequency* of recent logging with fresh stumps found in 56% and 24% of plots respectively. Some trees appeared to have been cut with power-saws, relatively costly implements, indicating **commercial use** rather than subsistence use of the wood.

This inventory wasn't designed to thoroughly assess timber extraction, however species and size distributions of observed stumps agreed previously noted **logging trends** (see Blackett, 1994; Wright, 1999; ASFMT, 2002). Older stumps were generally commercial timber species, such as *Brachyleana hulliensis* and *Afzelia quanzensis,* in larger dbh classes. Recently cut stumps were generally more currently abundant species, such as *Cynometra webberi* and *Manilkara sansibariensis*, of smaller sizes (*Table 9*). Estimated dbh values for old cut *B. hulliensis* trees reached over 60 cm, while only one live *B. hulliensis* tree had a dbh over 40 cm in the inventory plots. Although recently cut stumps of *B. hulliensis, Brachystegia spiciformis*, *M. sansibariensis, Oldfeldia somaliensis,* or *Pleurostylia africana* weren't found inside inventory plots, a fair number (62) of large trees of these species were seen freshly felled along access trails. A felled tree with a 30 cm dbh had created a 400 m^2 canopy gap.

Evidence of **charcoal burning** and cutting branches and smaller trees (3-20 cm dbh) for **poles** or **fuelwood** was observed in all major forest types (*Table 8*). Frequencies of fresh cutting were generally *greater* for *small* trees than for *large,* except in mixed thicket. Small tree cutting in **Cynometra and mixed forest** was *more frequent* in **forest** than **thicket** subclasses. Consistent with observed greater forest fuelwood demands on the eastern side of ASF (AFSMT, 2002), a *greater proportion* of **mixed forest plots** had old and fresh small tree stumps than sampled Cynometra areas to the west. In the **Brachystegia forest**, although no recent small tree cutting was seen, 50% of plots showed evidence of past extraction. In addition, forest guards and workers employed in construction at Kararacha forest station were seen cutting poles from Brachystegia areas, and, upon questioning, replied that the poles were to be used for the building (personal observation, 2004).

Table 8 **Anthropogenic disturbances observed in Arabuko Sokoke Forest, 2004**

fresh – appearing to have occurred in past 6 months **old** – appearing to have occurred more than 6 months ago. All stumps and cut branches with significant sprouting were deemed 'old.' (Plots in Madunguni are included)

Forest class	plots sampled	Number of plots in which evidence of anthopogenic disturbance was observed													
		medium -large (>20 cm dbh) **cut stumps within plot**				**medium-large cut stumps en route to plot** (within 200 m)				**polewood and fuelwood** (3-20 cm dbh) **within plot**				**charcoal burning**	
		old	% of sample	**fresh**	% of sample	**old**	% of sample	**fresh**	% of sample	**old**	% of sample	**fresh**	% of sample	**in plot**	% of sample
Brachystegia	22	4	18%	0	0%	9	41%	1	5%	11	50%	2	9%	1	5%
Cynometra	46	37	80%	7	15%	46	100%	15	33%	21	46%	12	26%	2	4%
forest	*25*	*22*	*88%*	*6*	*24%*	*25*	*100%*	*10*	*40%*	*15*	*60%*	*10*	*40%*	*0*	*0%*
thicket	*18*	*15*	*83%*	*1*	*6%*	*18*	*100%*	*5*	*28%*	*6*	*33%*	*2*	*11%*	*2*	*11%*
regenerating	*3*	*0*	*0%*	*0*	*0%*	*3*	*100%*	*0*	*0%*	*0*	*0%*	*0*	*0%*	*0*	*0%*
Mixed forest	27	15	56%	8	30%	21	78%	13	48%	16	59%	11	41%	1	4%
tall	*14*	*8*	*57%*	*3*	*21%*	*9*	*64%*	*7*	*50%*	*8*	*57%*	*7*	*50%*	*0*	*0%*
thicket	*9*	*5*	*56%*	*5*	*56%*	*9*	*100%*	*6*	*67%*	*7*	*78%*	*4*	*44%*	*0*	*0%*
regenerating	*4*	*2*	*50%*	*0*	*0%*	*3*	*75%*	*0*	*0%*	*1*	*25%*	*0*	*0%*	*1*	*25%*
other thicket	2	1	50%	0	0%	2	100%	0	0%	0	0%	0	0%	0	0%

Table 9 **Species, size, and age of cutting distribution for stumps occurring in and around inventory plots, Arabuko Sokoke Forest 2004** (Plots in Madunguni included)

Species cut	Stumps observed *within* inventory plots						Recently cut stumps observed *en route* to plots		
	Old			Recently cut					
	number in plots	% of total	mean dbh (cm)	number in plots	% of total	mean dbh (cm)	number observed	% of total	mean dbh (cm)
Brachyleana hulliensis	141	78%	27	0	0%	-	9	30%	20
Cynometra webberi	13	7%	21	27	90%	20	20	67%	22
Afzelia quanzensis	9	5%	38	2	7%	15	2	7%	33
Manilkara sulcata	5	3%	15	0	0%	-	0	0%	-
Manilkara sanzibarensis	4	2%	20	0	0%	-	16	53%	22
Combretum schumannii	2	1%	33	0	0%	-	0	0%	-
Hymenea verrucosa	2	1%	42	0	0%	-	0	0%	-
Nesogordonia holstii	2	1%	31	0	0%	-	0	0%	-
Cassipourea euryoides	1	1%	6	0	0%	-	0	0%	-
Croton pseudopulonellus	1	1%	5	0	0%	-	0	0%	-
Julbernardia magnistipulata	1	1%	23	0	0%	-	0	0%	-
Ochna thomasinana	0	0%	-	1	3%	4	0	0%	-
Brachystegia spiciformis	0	0%	-	0	0%	-	9	30%	41
Oldfieldia somalensis	0	0%	-	0	0%	-	2	7%	37
Pleurostylia africana	0	0%	-	0	0%	-	4	13%	44
TOTAL	**181**	old stumps in 97 plots		**30**	new stumps in 97 plots		**62**		

Spatial distribution of cutting reflects numerous factors, including accessibility, distribution of desired tree species and sizes, and likelihood of being caught and punished for illegal activity. While old sawmill logging was seen throughout the forest, recent felling of medium and large trees was found close to forest edges and main roads, predominantly on the eastern side of ASF and in Madunguni (*Figure 4*). On average, compared to plots without, plots *with* **fresh stumps** in or around them were *significantly closer* to:

- **forest edges** (mean *cut* plot 970 m *closer* than mean uncut plot, $p<0.01$)**,**
- **access trails/roads** (290 m closer, $p<0.01$)**,**
- **surrounding towns** (1,370 m closer, $p=0.01$)
- **forest stations** (3640 m closer, $p<0.01$)
- **guardposts** (1560 m closer, $p=0.01$).

This pattern was generally conserved when comparisons were done within each different forest type; however, fresh stumps in **Cynometra thicket** tended to be *further* from forest stations and guardposts (2331m further, $p=0.08$).

A similar pattern was seen for **pole** and **fuelwood cutting**. Fresh cutting was only seen within *1.5 km of the forest edge*. Compared to plots without, plots with fresh pole/firewood cutting in them were *significantly closer to:*

- **forest edges** (mean 1,250 m closer, $p<0.0001$)**,**
- **surrounding towns** (1,070 m closer, $p<0.01$),
- **forest stations** (1,660 m closer, $p=0.06$),
- **guardposts** (1,390 m closer, $p<0.001$).

Disturbance frequency inside and outside the **Nature Reserve** showed little difference in timber harvest despite different legal protections. **Fresh stumps** of medium-large trees were seen in 11% and near 78% of Reserve plots, roughly *the same frequencies* as outside the reserve (in 16%, near 78%). However, *no evidence* of recent **pole** and fuelwood cutting was seen in the reserve. **Madunguni,** historically having less use restrictions, was found to have a higher frequency of disturbance than ASF. Fresh pole and fuelwood cutting was seen in every plot. Medium to large trees were felled in the vicinity of every plot and fresh stumps were found in 67% of plots.

By estimating former biomass of cut trees for fresh stumps in inventory plots, **mean AGB carbon loss from recent cutting** was calculated. It was estimated that the forest as whole lost 0.5 ± 0.3 Mg C/ha Mg C/ha over the six months preceding the study, meaning a loss of 1 ± 0.6 Mg C/ha or a total of 420 ± 250 Mg C in 2004 due to illegal logging. The percent of extracted wood that was burned as fuel is unknown. This is also very likely an ***underestimate***: it leaves out cut trees with dbh under 5 cm and the carbon inventory plot structure, in which small trees/stumps were measured in small subplots, was not designed to accurately capture dispersed cutting of small trees. Using KIFCON's estimated wood volume removed in 1994 (Blackett, 1994) and the mean wood density for species observed in ASF (0.6 g/cm^3), roughly 820 Mg C was removed from ASF for timber and carving, 600 Mg C for poles, and 1,480 Mg C for fuelwood in 1994. **Cynometra thicket** was found to have the greatest average annual AGB biomass loss (1.5 Mg C/ha/yr), followed by Cynometra forest (0.8 Mg C/ha/yr), and mixed forest (0.1 Mg C/ha/yr). Cynometra thicket and forest within **Madunguni** had *very high* biomass extraction rates with an estimated 14.6 Mg C/ha/yr and 8.1 Mg C/ha/yr in AGB removal respectively.

4.5 Carbon density co-factors

a. Soil characteristics, position, & elevation

The distribution of ASF **forest types** is related to the spatial distribution of soil type, elevation, and precipitation. Because ASF forest types were found to have different carbon densities, these factors do influence forest carbon distribution. However, carbon density also varied *within* each forest type area. In general, at this sampling intensity, plot **elevation**, **east-west** and **north-south** positions did not significantly influence *total* or *tree carbon density* variations within forest types, however these factors did detectably influence ***soil carbon***:

Cynometra*: soil carbon* increased *slightly with elevation ($r^2 = 0.09, p = 0.06$) and* decreased *moving northward ($r^2 = 0.25, p = 0.0005$) and eastward ($r^2 = 0.14, p = 0.01$)*
Mixed forest*: soil carbon* increased *with elevation ($r^2 = 0.12, p = 0.11$) and* increased *moving northward ($r^2 = 0.17, p = 0.05$) and eastward ($r^2 = 0.17, p = 0.05$)*

Forest types were closely related to **soil type** (*Appendix C*). Observed soil types varied in carbon densities with means ranging from 14 ± 2 Mg C/ha for pale orange sands to 30 ± 7 Mg C/ha for red silts. Soil type and carbon did vary *within* each forest type, especially at forest type borders; however, most *soil carbon density* differences were *not* statistically significant at this sampling intensity and had little effect on *total carbon* compared to vegetation. Most **Cynometra forest** plots had 'brown/red' soils, found at higher elevations (mean 58 m higher, $p<0.05$) than 'red.' Most **thicket** had 'red' soil. Despite *higher tree biomass* on brown/red soil than red (8 Mg C/ha, $p<0.1$), no significant soil carbon differences were seen based on the color difference. If the AGB difference was soil and/or elevation driven, it may be due to properties not quantified here (moisture, other soil nutrients, etc).

Brachystegia plots on **borders with other forest types** had high *total* carbon densities and different soil types from the pale sands of other **Brachystegia** areas: 111 Mg C/ha on red silt/sand bordering Cynometra and 92 Mg C/ha on brown sand bordering mixed forest. However, high total carbon was due to *high tree biomass*, with no notable difference in soil carbon. These areas supported both large *B. spiciformis* trees and a dense understory of smaller trees seen in the other forest types. **Mixed forest** plots close to Cynometra had brown/red and red silt/clay soils with *higher soil carbon* than the brown sandy soils of other mixed forest, but, due to *lower tree biomass* on these redder soils, the *total* carbon density was *lower*.

In soil types observed, **soil bulk density** *increased* with depth while **carbon content** *decreased* with depth, likely reflecting the influence of organic carbon inputs from decomposed litter at top layers. A weak but significant, negative relationship ($r^2 = 0.25$, $p<0.001$) was seen between increasing bulk density and carbon content (% C) in the top 10 centimeters. Results imply that, without forest cover's continual **litter input**, carbon density in ASF soils would decrease. Evidence of this was observed in KEFRI's sampling of cleared agricultural areas around Madunguni: carbon densities to 30 cm depth Madunguni forested areas in this study (16-28 Mg C/ha), were generally *higher* than those seen in surveyed agricultural soils (8-14 Mg C/ha) in farms in Kakyuni and Jilore sublocations, with higher bulk density and lower percent carbon concentration than the forest (Mchua & Lelon, 2004).

b. Anthropogenic disturbance

Observed anthropogenic disturbances had a notable effect on carbon density. Effects of **timber, pole,** and **fuelwood cutting** on carbon densities were assessed using both the *occurrence* of cutting and the estimated *biomass lost* from cutting. In some forest types too few plots with or without stumps were measured to determine significant relationships. No Brachystegia plots contained fresh stumps, although fresh felling was observed in the area. Only *one* Cynometra thicket plot had *fresh* stumps. *All* Cynometra forest plots had *old* stumps in them or nearby. In general, *within* a forest type, *AGB* and *total carbon densities* were *lower* in plots with ***fresh* medium to large stumps** than in plots without fresh stumps, regardless of old stumps (*Figure 5*). 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). ***Old stumps*** were too widespread to make significant comparisons, however in the absence of new stumps, old stump plots generally had lower carbon densities. In **Brachystegia forest**, plots with old stumps in them tended to be at Cynometra edges where primary commercial timber species were more frequently found. However, as transitional Brachystegia areas had higher tree biomass due to their mixed canopy composition, they retained higher AGB carbon than other Brachystegia plots despite having more disturbance.

Carbon densities in plots *with* and *without* **new or old pole and fuelwood cutting** were very similar in all vegetation classes with differences not greater than 3 Mg C/ha, none of which were statistically significant. However, a trend of lower carbon density in plots with fresh polewood cutting was consistent throughout the forest classes.

Figure 5 Carbon densities estimated from means of inventory plots. Error bars indicate 95% confidence interval. Bars without error bars indicate a logging intensity class for which there was only one plot observed in a forest class.

Linear regression showed *negative* relationships between **local illegal logging intensity** (plot biomass removal) and both *AGB* and *total carbon density* across all forest types. However, the weak relationships, low r^2 values and coefficients, (example: *Figure 6*) indicated little of the carbon density variation was explained by this illegal logging indicator. Other factors influencing carbon density, not controlled for in this study, may have drowned out signs of logging influence. Only in the **mixed forest** was there a *statistically* detectable and sizeable relationship (r^2=0.19, p=0.03, *AGB Mg C/ha = 45.1 Mg C/ha - 0.85 (removed AGB MgC/ha)*). Splitting broad forest types into subclasses strengthened the relationship for **mixed thicket** (r^2=0.35, p=0.09, *AGB Mg C/ha = 35.2Mg C/ha - 0.62(biomass logged MgC/ha)*). It is possible illegal logging had a greater impact on the carbon density of this forest type than others.

The effects of **distance from forest edges, towns, roads,** and **guard posts** on *plot carbon* were consistent with their relations to logging, pole, and firewood cutting. Again effects were small relative to other sources of variation. The most discernable relation was *increasing* mixed forest AGB carbon with *increasing distance* from forest stations (r^2 = 0.22, p =0.01). Of these factors, the one with the largest effects on *total carbon density* in was distance from **forest edge** (r^2=0.18, p=0.05, *increasing further from edge*) for **Brachystegia** forest and distance from **forest stations** (r^2=0.15-0.14, p=0.05, *increasing further from stations*) in **Cynometra forest** and **mixed forest**.

Unexpectedly, *tree AGB carbon* density *decreased* with distance from **old sawmills** in Cynometra and mixed forest (excluding old cleared mill yards) and *increased* with distance from **forest stations**. *AGB biomass* contributions from *larger* dbh classes (30 cm and above) actually *decreased* with distance from sawmills. This could be coincidental, perhaps due to the *internal* positions of the sawmills and *edge* locations of forest stations. It was consistent with recent disturbance patterns: *fresh* stumps were more frequently found nearer edges and forest stations and further from old sawmills.

Kelsey and Langdon used 1983 ASF aerial photographs to classify areas either **primary** or **secondary forest** based on discernable logging damage (Kelsey & Langdon, 1984). This area classification was used to look at the effect of **historic logging**. Plots in areas considered ‘primary’ in 1983 had significantly *more biomass removal from old logging* in the Cynometra and mixed forest (5 – 7 Mg C/ha more removed, p=0.05). However, no significant differences in 2004 *AGB* or *total carbon density* were established. This may indicate regeneration in the secondary areas and/or continued logging in the primary areas since 1984.

4.6 Total carbon stock and changes over time

a. ASF carbon stock in 2004

Total carbon stock estimates for the indigenous forest area in Arabuko Sokoke Forest range from 2.8-3.0 Tg C. A *sensitivity analysis* was used to assess the effect of using different area estimates and cover classifications to calculate carbon stock (*Table 10*). Splitting forest types into **subclasses** did *not* produce significant differences in total stock compared to the level of uncertainty in the stock estimate, but it did decrease the 95 % confidence interval. Results indicate that, due to uncertainty in area figures, ASF total carbon stock in 2004 should be quoted as **3.0 Tg ± 0.2 Tg C**

With 2004 **Landsat image classification** areas, the most general forest type classification produced the highest carbon stock estimate with the highest level of uncertainty: 3.08 ± 0.17 (6%) Tg C. Separating ‘other thicket’ from the Cynometra class, brought the total estimate down by 0.04 Tg C. Separating thicket and forest subclasses brought the total back up by 0.02 Tg C and decreased uncertainty. Because classification accuracy was low for differentiating mixed thicket vs. tall forest, only using a Cynometra forest/thicket divide may be used with reasonable confidence.

Different forest cover area estimates from **previous studies** produced more significant differences in total carbon stock. Sources differ on the total amount of forested area in ASF. Aerial photo interpretation from 1983 (Kelsey & Langton, 1984) yielded 37,200 ha of forest and 2.81 ± 0.15 (5%) Tg C while that from 1992 (Butt, 2000) yielded 40,706 ha of forest and 3.06 ± 0.18 (6%) Tg C. This may represent regeneration over time and/or a change in the classification of forest or non-forest. Comparing the 1992 and 2004 Landsat scenes revealed no significant change in the area *covered* by indigenous forest inside ASF in this period. Nevertheless, a change in carbon stock could have occurred: *carbon densities* within the forested area may have changed due to a changing balance of regeneration and extractive use.

Table 10 Area estimate and forest classification method sensitivity analysis for calculating total carbon stock in Arabuko Sokoke Forest

Different classification systems and area estimates for land cover in ASF from various sources are used to calculate the total carbon stock in ASF. The range of resulting values indicates the uncertainty range introduced by the choice of classification and area determination methods.

Most basic classification: 3 classes, "other thicket" assumed to be the same as Cynometra

forest type	carbon density (Mg C/ha)	95% CI	Kelsey & Langton, 1984			ASFMT Report, 2002			Bilal Butt 1992 photo interpretation			J.Glenday 2003 Landsat classification		
			area *(ha)*	**carbon** (Tg C)	95% CI	***area*** *(ha)*	**carbon** (Tg C)	95% CI	***area*** *(ha)*	**carbon** (Tg C)	95% CI	***area*** *(ha)*	**carbon** (Tg C)	95% CI
Brachystegia	79.7	6.2	*6,700*	0.53	0.04	*7,700*	0.61	0.05	*7,740*	0.62	0.05	*7,714*	0.62	0.05
Cynometra	73.7	6.0	*25,300*	1.86	0.15	*23,500*	1.73	0.14	*25,500*	1.88	0.15	*25,621*	1.89	0.15
mixed forest	77.7	12.0	*5,200*	0.40	0.06	*6,300*	0.49	0.08	*7,250*	0.56	0.09	*7,140*	0.56	0.09
TOTAL			***37,200***	**2.80**	0.17	***37,500***	**2.83**	0.17	***40,490***	**3.06**	0.18	***40,476***	**3.06**	0.18

Differentiating 'Other thicket'

Brachystegia	79.7	6.2				*7,700*	0.61	0.05	*7,740*	0.62	0.05	*7,714*	0.62	0.05
Cynometra	73.7	6.0				*21,200*	1.56	0.13	*23,530*	1.73	0.14	*23,491*	1.73	0.14
mixed forest	77.7	12.0				*6,300*	0.49	0.08	*7,250*	0.56	0.09	*7,140*	0.56	0.09
other thicket	57.7	1.3				*2,300*	0.13	0.00	*1,970*	0.11	0.00	*2,130*	0.12	0.00
TOTAL						***37,500***	**2.80**	0.16	***40,490***	**3.03**	0.17	***40,476***	**3.02**	0.17

Differentiating Cynometra thicket from forest

Brachystegia	79.7	6.2	*6,700*	0.53	0.04	*7,700*	0.61	0.05				*7,714*	0.62	0.05
Cyn. forest	83.4	7.7	*12,200*	1.02	0.09	*9,900*	0.83	0.08				*12,157*	1.01	0.09
Cyn. thicket	64.9	6.5	*13,100*	0.85	0.08	*11,300*	0.73	0.07				*11,334*	0.74	0.07
mixed forest	77.7	12.0	*5,200*	0.40	0.06	*6,300*	0.49	0.08				*7,140*	0.56	0.09
other thicket	57.7	1.3		0.00	0.00	*2,300*	0.13	0.00				*2,130*	0.12	0.00
TOTAL			***37,200***	**2.81**	0.15	***37,500***	**2.80**	0.14				***40,476***	**3.04**	0.15

Differentiating tall mixed forest from mixed forest thicket

Brachystegia	79.7	6.2										*7,714*	0.62	0.05
Cyn. forest	83.4	7.7										*12,157*	1.01	0.09
Cyn. thicket	64.9	6.5										*11,334*	0.74	0.07
mixed tall	94.2	15.9										*3,530*	0.33	0.06
mixed 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

b. Madunguni carbon stock 1992 - 2004

Comparing satellite image classification for 1992 and 2004 it was found that the Madunguni area had roughly 780 ha of Cynometra thicket/forest and Brachystegia-like woodland in 1992, but **lost 86% of this forest cover** (670 ha) in 12 years (*Table 11, Figure 7*). To make a *conservative* approximation of the **carbon stock change**, the following *assumptions* were made:

- Soil pool stocks and the more minor carbon pools did not change significantly
- AGB carbon densities in non-treed land cover types were relatively insignificant
- Cover types with partial tree cover but no closed canopy, treed shambas (farms) and open woodlands, were given the AGB carbon density estimated for miombo woodland (19 Mg C/ha,Woomer, 1993), open tree cover type found in similar temperature and rain conditions.

Using these assumptions, Madunguni ***lost roughly 20,000 Mg C (0.02 Tg C)*** *in1992 to 2004.*

Charred ground, charcoal pits, and smoking tree stumps observed throughout Madunguni suggested that much of the removed biomass was *burned* in land clearing or for fuel, and was therefore emitted to the atmosphere. Using recent carbon price estimates ($3-5/Mg C), *offsetting an emission of 20,000 Mg C would be worth $80,000.* It can be assumed that *greater* emissions have occurred, or will occur, due to loss of stored soil carbon as the land is farmed (Woomer, 1993). Based on differences between forest soil and agricultural soil (*see 4.5.a above*), Madunguni soil carbon stocks may be 6,000 Mg C or more below potential. More detailed soil assessments are necessary to determine how much of the observed differences result from agricultural use or pre-existing variations in the soils.

Table 11 Land cover change and estimated carbon stock change for Madunguni Forest 1992 – 2004

Area estimates made using classification of Landsat images. Aboveground biomass (AGB) carbon densities for tree cover types were assumed to be the same as seen in ASF. Open woodland cover types with sparse tree cover were assigned AGB carbon density from miombo woodlands (Woomer, 1993). Non-treed cover types were assumed to have insignificant AGB stocks. Total figures rounded to two significant digits to account for uncertainty. (* Brachystegia-like woodland)

cover type	***AGB carbon density***		**1992**				**2004**				**Change '92-'04**			
	Mg C/ ha	*95% CI*	***area (ha)***	*% of total*	**AGB carbon** (Mg C)	*95% CI*	***area (ha)***	*% of total*	**AGB carbon** (Mg C)	*95% CI*	***area (ha)***	*% change*	**AGB carbon** (Mg C)	*95% CI*
Brachystegia *	*46*	*5*	*65*	*8%*	3,000	330	*15*	*2%*	700	80	*-50*	*-77%*	-2,300	330
Cyn. forest	*42*	*6*	*190*	*22%*	8,060	1,150	*20*	*2%*	860	120	*-170*	*-89%*	-7,200	1,160
Cyn. thicket	*28*	*5*	*520*	*61%*	14,610	2,610	*72*	*8%*	2,000	360	*-450*	*-86%*	-12,600	2,630
treed shamba	*19*	*2*	*6*	*1%*	110	10	*85*	*10%*	1,610	170	*79*	*1340%*	1,500	170
open woodland	*19*	*2*	*20*	*2%*	370	40	*58*	*7%*	1,100	110	*38*	*194%*	730	120
road/bare			*37*	*4%*			*0*	*0.02%*			*-37*	*-100%*		
sand			*0.4*	*0.05%*			*3*	*0%*			*3*	*666%*		
shrub/grassland			*13*	*2%*			*600*	*70%*			*590*	*4405%*		
grass			*0.0*	*0.00%*			*0.1*	*0.01%*			*0*	*350%*		
FORESTED AREA			*780*	*91%*			*100*	*13%*			-670	*-86%*		
TOTAL			*860*		**26,000**	2,900	*860*		**6,300**	440			**-20,000**	2,900

5. Conclusions: Potential for carbon offset projects

5.1 Potential to increase carbon stocks

a. Increasing *forest cover* in and around ASF

Little ASF forest has been completely cleared in recent decades. Former sawmill and mining areas had open canopies and low biomass densities, but appeared to be regrowing with saplings and small trees of dominant forest species, *C. webberi* and *M. sansibariensis*. **Enrichment planting** could increase growth, but the total area is small (<500 ha) making a relatively small carbon gain. Forest gaps caused by recent logging tree falls may constitute a larger 'deforested' area, but planting in scattered gaps could store less carbon than emitted from petrol used to drive throughout ASF for planting, weeding, watering, and monitoring.

Opportunities for reforestation and afforestation exist in areas around ASF. The recently gazetted **Madunguni Forest** has been largely cleared and could be the site of a reforestation project, which could also provide employment and benefits for relocated communities from the area. As the Madunguni forest clearance occurred after 1990, such a project could only sell carbon credits to the voluntary market, not the CDM. Reforestation projects in some of the other **trust land** areas held by County Councils, could similarly help address local needs for forest products. If tree planting helped local communities meet their resources needs, it could reduce pressure on ASF and allow regeneration of carbon stocks.

Planting fast-growing commercial exotic species such as *Casuarina spp* or *Mangifera indica*, on lands outside the forest, on either public land or on land of any willing farmers, could both accrue carbon credits and supply wood needs if sustainably managed. In terms of supplying fuelwood needs, carbon storage will not be achieved if the rate of burning exceeds the rate of tree growth. **Intercropping** fast growing trees with relatively slow growing **indigenous species** could speed short-term project returns at the same time as aiding regeneration of indigenous forest in the long-term.

b. Increasing *carbon densities* within ASF

Results of this study and previous inventories give substantial indication that the *biomass carbon densities* seen in ASF forest types are ***below their potential and could be increased***:

- Evidence of **past logging of *large* commercial hardwood trees** in is widespread in ASF and biomass differences remained between plots with and without old stumps (*Figures 4,5*). Old stumps had diameters larger than those of living trees (Blackett, 1994; Wright, 1999). Tree biomass increases exponentially with diameter, so the *presence or absence of large trees*, even at low densities, has a pronounced effect on carbon density (Chave et al., 2003; Keller et al., 2001; Brown et al., 1995; Clarke & Clarke, 1996).

- **Continued illegal logging** of medium to large trees was seen throughout ASF: 30% of the inventory plots contained fresh stumps. Plots with fresh stumps had *lower* biomass than without (significantly lower by 34 and 16 Mg C/ha in mixed and Cynometra forest). Compared old stump frequencies, *recent cutting increased* in **mixed forest**. Based on stumps in inventory plots alone, it was estimated that 1 Mg C/ha/yr or more was removed from ASF in 2004. This is a significant amount: the annual growth in tropical *moist* forests, which would grow faster than *dry* ASF, is estimated to only sequester 0.35-1.3 Mg C/ha/yr (Clarke & Clarke, 2000). *Depending on how much wood removed from ASF is burned, it is possible that ASF is a* ***net carbon source*** *rather than a sink or store.*

- **Pole** and **fuelwood cutting** of smaller trees was seen to have a consistent negative effect on AGB carbon in all forest classes. Although the effect was small compared to the effect of logging larger trees, given the slow growth rate of dry forests and human population growth around ASF, it is likely that the effects of small tree harvesting on biomass densities will become more prominent with time.

- The **thicket/forest subclasses** seen within Cynometra and mixed forest types showed significantly different carbon densities. These divisions may result from climactic and edaphic features, which appeared to be the case for Cynometra. It is possible the **mixed thicket** class was separated from tall mixed forest as a result of human disturbance: mixed thicket plots generally the same soil as taller forest, but thicket areas had higher frequencies of logging evidence (*Table 8*) and AGB biomass removal (13.5 vs. 5.3 Mg/ha). If 'mixed thicket' is disturbed mixed forest, it could attain tall mixed forest AGB.

- Except for Brachystegia and tall mixed forest, mean AGB carbon densities in ASF were *lower* than the predicted **potential for physical conditions of African dry forests**: (46 Mg C/ha, Brown & Gaston, 1995).

Depressed carbon density in ASF forest types means the carbon stock *within* ASF is lower than it could be if continuing biomass removal was prevented. However, *not all of the carbon removed from ASF was emitted to the atmosphere*. Burned biomass in **fuelwood** and **charcoal** emits CO_2 to the atmosphere. **Non-fuel timber products store carbon**, but are ***not* carbon sinks** like growing trees that continually photosynthesize and take in carbon. *Preventing illegal logging does have potential to increase net carbon storage of the current situation, but it is contingent on many factors.*

It is likely that much of the wood from *larger trees* cut in ASF used for building and carving. KIFCON estimated that almost half the volume of wood removed in 1994 was used for non-fuel timber products (4,980 m^3 for fuelwood and 4,740 m^3 for poles, timber, and carving wood). Extraction of **non-fuel products** *can* result in **decreased net carbon storage over time** *if* the rate of carbon accumulation in *regenerating disturbed forest* is slower than the rate of carbon accumulation the *forest would have if undisturbed*. Previous studies reported unsuccessful regeneration for certain ASF species (Davies, 1992; Wright, 1999), but long-term studies of overall biomass accumulation in damaged areas have not been done.

A reduction in fuelwood cutting in ASF would only result in a *net* increase in carbon storage *if* the amount of ***leakage*** (the carbon lost from other areas if ASF restrictions result in increased unsustainable harvesting in outside ASF) is less than the carbon stock increase within ASF. For a harvesting reduction project to ensure net carbon storage, it would have to include activities addressing community resource needs. Previous studies have suggested activities that would help offset leakage: (Kelsey & Langton, 1984; Davies 1993, Wright, 1999, ASFMT, 2002)

- Providing/fostering alternative incomes and resource options
- Participatory forest management (PFM) with sustainable harvest plans
- Reducing markets for illegal wood products
- Dissemination of fuelwood saving techniques and technologies

During this commitment period of the Kyoto Protocol (2008-2012), only tree planting afforestation and reforestation (AR) projects will be considered for land cover CDM projects. Improved management and deforestation prevention activites, such as those listed above, can only receive carbon funding from voluntary markets.

5.2 Additionality concerns

To actually offset carbon emissions and sell CERs, a carbon storage project must be ***additional* to what would otherwise occurred**. The project proponents must prove this by providing a reasonable **baseline scenario,** forecasting future carbon stock changes without carbon funded project activities. Activities already mandated by the government or activities that would be economically beneficial regardless of the carbon markets won't be considered additional. Project activities that could reasonably sell 'additional' carbon credits include:

employing more effective means or technologies for expediting existing directives (such as illegal logging prevention) than could otherwise be used
initiating carbon storing activities that could produce profit in the long term but for which start-up funds can't be easily accessed (often the case in agroforestry),
expanding of already initiated AR activities that would not likely be expanded otherwise (have not produced profits with which to do so)

Rehabilitation, and improved management project directions have already received written support from NGOs, the government through Kenya's Forestry Master Plan, and the ASFMT through the ASF management plan. Despite this **expressed willingness** at the national and regional level, persistant **local barriers** to project execution include:

engaging resource-strapped communities in projects with relatively long-term payback,
population growth with limited arable land and limited employment opportunities enhancing reliance on essentially 'free' and 'instant' forest resources
capacity or local motivation to increase efficiency in forest monitoring and patrolling,
lack of experience and/or precedent for rearing indigenous species for AR activity,

Addressing these barriers could be considered 'additional.' The 'baseline' for ASF would likely include continued illegal harvesting. Rates of biomass extraction may change as large trees become scarce, but pole and fuel extraction rates are likely to continue. Plans do exist to decrease pole and fuelwood extraction to sustainable levels by extending the PFM program initiated in Dida, but this is contingent on funding. Given the indications of unsustainable harvesting rates, it seems reasonable to assume that without further intervention, ASF carbon would stay at 2004 levels, if not decline, as shown in a very rough calculation:

[(1 MgC/ha/yr *removed*)* (50% *is fuel*)] = 0.5 MgC/ha/yr estimated emission
– 0.4 MgC/ha/yr estimated forest accumulation
= 0.1 Mg C/ha/yr emitted

5.3 Project scenarios

The following scenarios indicate the magnitude of carbon storage increases possible in ASF and the value of these on the carbon market, to be compared with the *benefits, drawbacks,* and *costs of project implementation*. Actual project designs created in stakeholder meetings would take into account preferences, practicalities, and cost-benefit analyses that are beyond the scope of this study. After specific project activities have been outlined, a ***project area specific* baseline** needs to be estimated. Carbon density estimates from this study can be incorporated in project proposals, however ***project area specific* monitoring** will also be needed during the project's lifetime.

a. Estimating forest growth rates

At the time of study, no analyses of long-term growth data in ASF had been completed. KEFRI was in the process of compiling data from plots sampled in 1993 and 2003, which should yield some estimates of net biomass accumulation rates in ASF. Lacking this, growth estimates (*Table 8*) were made using inferences from existing information.

Monitoring seven years of *B.hulliensis* growth in forest conditions on red soils in Tanzania showed a mean dbh increase rate of 0.12 cm/year for trees of a starting dbh range of 17-56 cm (Willan 1963, Borota, 1967). In a study of growth rates of trees in the dry forests of the Shimba Hills, Kenya, dbh annual increments for trees with dbh<20 cm were found to be half to two thirds of those seen for larger trees in mature forest (Kahumbu, 2002). To make *rough, conservative* estimates of **growth rates** *(Table 8)* in ASF forest types, a 0.12 cm/yr dbh increase was applied to trees dbh 20–60 cm and a 0.06 cm/yr to all smaller trees in the tree stock measured in this inventory. Annual increases in AGB due to this growth were calculated until annual increments stabilized.

It was expected that carbon accumulation rates in ASF would be lower than those found in moist tropical forests, 0.35 Mg C/ha in mature and 1.3 MgC/ha for young growing (Clark & Clarke, 2000). The resulting estimates were higher than expected for a mature forest (>0.35) but within the expected range for a younger forest. However, due to heavy disturbance ASF forest types do a have young forest-like structure with high densities of small trees. To check these growth estimates, it is assumed that the sampled area in the Dida sawmill yard started growing from a tree-less state and had been growing for 40 years. If this were so, the 11 ± 6 Mg C/ha in live tree AGB and BGB in regenerating Cynometra plots roughly indicates a 0.3 Mg C/ha/yr increment.

Table 12 Application of estimated tree carbon stock growth increments to Arabuko-Sokoke Forest to approximate carbon accumulation through natural regeneration

Growth increments were calculated by applying dbh growth increments measured in other studies of African dry forest trees to the tree stocks sampled in this study and taking the 10 year average increment of increase in C storage. Potential carbon densities were estimated from mean carbon densities in plots lacking evidence of tree cutting, recent or historical. For Brachystegia forest, the difference between carbon densities in the disturbed plots was not significantly different from the undisturbed.

Forest type	Area (ha)	AGB carbon density (Mg C/ha)				estimated growth increment (Mg C/ha/yr)	years to reach potential	stock increase expected (Tg C)	95% CI
		actual (mean)	potential (undisturbed)	difference	95% CI				
Cynometra forest	*12,157*	41.9	63.8	21.9	16.4	0.46	47	0.27	0.20
Cynometra thicket	*11,334*	27.7	28.9	1.2	7.2	0.36	3.3	0.01	0.08
Mixed forest (all)	*7,140*	38.4	53.5	15.1	10.4	0.36	42	0.11	0.07
mixed tall forest	*3,530*	50.0	62.2	12.2	9.2	0.44	27	0.04	0.03
mixed thicket	*3,610*	26.8	53.5	26.7	10.4	0.32	82	0.10	0.04
Other thicket	*2,130*	22.8	26.6	3.8	6.0	0.39	9.9	0.01	0.01
TOTAL:							*using mixed forest mean:*	**0.40**	**0.23**
							split mixed forest/thicket:	0.43	0.22

b. Logging prevention

Preventing continued illegal logging *could* increase forest carbon densities and *net* carbon terrestrial stock, by preventing carbon emissions from wood burning, allowing natural regeneration, and possibly preventing depressed growth rates as described above (*5.1.b*). Because there were so few undisturbed forest areas for comparison, the **potential mean carbon densities** that ASF forest types could reach are speculative. In this scenario the potential carbon storage (*Table 8*) was estimated from the *mean AGB* and *BGB* carbon densities seen for plots with no evidence of logging. Mean carbon densities for the other forest carbon pools did not show significant differences with or without disturbance so it was assumed these would not change significantly with protection.

Applying estimated growth rates to the areas covered by each forest type indicated that it would take roughly 50 years for all forest types to achieve their potential AGB carbon density. This would constitute a **0.40 ± 0.2 Tg C increase** in ASF forest carbon stock *over 2004 stock.* Assuming CER credit prices at $4/MgC, this storage is worth roughly **$1.6 million** ($32,000/yr if evenly spread over 50 years). If the mixed thicket class has the potential to reach mixed forest carbon densities then carbon stocks could increase by 0.5 Tg C, but this could take more than 80 years. If ASF carbon stocks were predicted to decline without extra intervention, gains could be larger.

Halting illegal logging without addressing timber needs could result in **leakage** from increased harvesting outside, reducing the net effect. Gains of this size are smaller than those for many currently funded carbon offset projects, however a reduced impact logging project in Malasaya and a USAID funded forest protection project in India reported carbon stock similar increases of 0.4-0.6 Tg C (*see Table 1*).

c. Forest Zonation with PFM

Forest zonation has been suggested in both the KIFCON reports of the early 90's and in the recent ASF Management Plan (Davies, 1993; Blackett, 1994; ASFMT, 2002). Buffer zones on forest borders would be established as sustainable use zones in which local communities could harvest polewood, fuelwood, and medicinal plants, while the forest interior would be a strictly non-extractive use zone. The ASFMP suggests the community use buffer zones be managed through participatory forest management (PFM) in which communities design sustainable harvest plans in conjuction with the ASFMT.

This scenario could increase the total carbon stock of the forest by allowing natural regeneration in the protected core areas while halting further over-harvesting and carbon density decline in the buffer zones. Optimistically this scenario could yield similar carbon stock gains to the logging prevention scenario, around 0.4 Tg C, by increasing mean AGB carbon densities, but it also has other advantages.

In the stopped logging situation above there is high likelihood for **leakage**. PFM is one way of addressing this by permitting traditional land-use practices at a sustainable level rather than criminalizing them. It was evident that the level of patrolling and law enforcement provided from centralized organization at the forest station was not effective in eradicating illegal logging. Having on-site, constant, village level enforcement of sustainable harvests may be a more effective, economical, and practical means of preventing illegal logging in the long term.

The **Dida sublocation**, on the western side of ASF, was selected as the area for a trial PFM project. At the time of study, the DIFAAFA and ASFMT were preparing a sustainable harvesting plan for a 3 km deep by 14 km long community use zone at the forest border to supply the 3 villages in this area. Fuelwood collection was planned to be limited to a 1 km wide strip inside the forest located 1 km from the forest edge and only 30% of the estimated fuelwood demand was to be obtained from the deadwood in the forest (Mbuvi et al, 2004).

To assess the effects of this plan on the forest's carbon stocks it is necessary to **compare extraction rates and wood burning rates to forest growth rates**. The average headload size found in past FAO wood use surveys in Kenya was 25 kg (FAO, 1983), but current values for Dida may differ. A variety of headload sizes were evaluated to estimate the rate of fuelwood offtake from the forest under the Dida plans to estimate the amount of forest wood to be burned *(Table 13*).

If the average headload is 25 kg or less it appears that the **release of carbon from forest fuelwood**, roughly 0.46 MgC/ha/yr, might be equal to or less than estimated carbon accumulation rates for Cynometra forest, the cover type which dominates the PFM area (*Tables 12 & 13*). If greater amounts of fuelwood are taken, it is possible that the Dida plan could be *emitting* ASF carbon faster than it accumulates in the harvesting zone. Reduced pressure on other areas of the forest would allow growth in those areas, which may offset the fuelwood use rates. Continued monitoring, enforcement of zoning, and greater knowledge of local growth rates would help ensure permitted fuelwood off-take levels are either equal to below carbon accumulation rates in the area so that the project is carbon neutral or, better, carbon storing.

Table 13 Estimating carbon offtake per hectare for fuelwood use in Dida sublocation according to PFM planning

Because a mean headload size estimate for all of Kenya may not apply to the current situation in Dida, a number of sizes were considered.

* Fuelwood demand in number of headloads was estimated by surveys performed by the ASFMT and DIFAAFA. Planning documents indicate 30% of this demand is to be met by the forest, harvested from a 1 km wide strip that runs the length of the 14 km PFM area forest boundary (Mbuvi et al., 2004)

average headload weight (kg)	**average headload biomass** (kg - dry)	**average headload carbon** (kg C)	**fuelwood demand** (headloads / yr)*	**fuelwood demand from forest** (headloads / yr)*	**Carbon in consumed fuelwood** (Mg C / yr)	**Fuelwood cutting area** (ha)*	**Carbon stock removal** (Mg C/ha/yr)
25	20	10	215,200	64,560	650	1,400	0.46
15	12	6	215,200	64,560	390	1,400	0.28
5	4	2	215,200	64,560	130	1,400	0.09

Dida is on the west side of ASF. Expanding PFM to areas on **the eastern side** of ASF may be *more difficult to establish*, as forest resource dependency and harvesting rates were higher there, but also have a *greater carbon payoff*, because the baseline scenario would have a more depressed carbon density and the mixed forest area in the east have higher potential carbon density.

d. Reforestation of Madunguni

Land cover changes indicate that the Madunguni Forest area lost roughly **0.02 Tg C** or more between 1992-2004 (*section 4.6.b*). The estimated value of this carbon if marketed as carbon credits is $80,000. Reforestation activities could restore the amount of carbon that was lost. Assuming mean AGB carbon accumulation rates estimated for Cynometra forest and thicket (*Table 12*) it may take over 70 years for the forest to regenerate on its own and reach mean carbon densities seen in the rest of ASF. This translates into carbon credit funding of $1,140 per year if divided evenly if natural regeneration were considered 'additional.'

Net carbon storage for projects in Madunguni depends on the **projected baseline scenario**. As the forest has been gazetted as a Forest Reserve, inhabitants of the area may be relocated in the future, but mechanisms and timelines for this were uncertain at the time of study. Madunguni had the highest concentration of fresh illegal logging evidence, ongoing charcoal production, and recent instances of forest clearance observed in this study. Due to uncertain tenure issues, it is likely that this activity will continue at high rates until people are relocated and/or forest management activities are implemented. Community members are aware that their income from the forest resources and land may soon end. Some may have decided to harvest timber and produce charcoal at high rates to profit as much as possible before resource access disappears. A baseline situation might then be continued degradation followed by a period of natural regrowth. Alternatively, if current plans for the Madunguni communities include adequate incentives to preserve the remaining forest or enforced prohibition of further cutting, it is possible that the 2004 forest cover estimates could be the baseline with possibilities natural regeneration.

Carbon storing project activities that may be considered *'additional'* include:

- planting indigenous tree seedlings in open areas to speed regeneration,
- agroforestry promotion on farms if any agricultural areas are to remain,
- initiation of timber or fuelwood plantations or woodlots in the area to lessen the need for further forest harvesting.

Planting of timber, fuelwood, or other agroforestry species would speed the rate at which carbon is stored as these species often have higher growth rates making a more suitable time scales for investors (often 30 years or less). Extra care would be needed to ensure sustained carbon gains. In the case of fuelwood, the rate of use would need to match or be lower than tree growth rates for a carbon neutral or carbon storing project. Agroforestry plantings on farms would *not* be likely to reach the carbon stock increases that could be achieved by restoring dense tree cover; however, other products from these trees may make a project more lucrative.

One possibility would be to **intercrop faster growing commercial species with indigenous trees**. This could speed carbon accumulation rates, gain shorter-term economic benefits from an initial harvest of tree products, and increase indigenous forest cover in the long run. In reforestation trials on degraded pastureland in Costa Rica, intercropping indigenous trees with nitrogen fixing agroforestry species was found to improve survival of native species, while addition of chemical fertilizers did not (Carpenter et al., 2004). However, allowing continued extractive or agricultural uses of areas within Madunguni will require careful negotiations, monitoring, and possibly enforcement to prevent continued harvesting of high value indigenous forest trees.

The net carbon stock increase likely for Madunguni is relatively small compared to currently funded AR projects, however a simplified methodology for **small scale AR projects** will be set up for the CDM for projects with net carbon benefits 2,000 Mg C/yr (8,000 Mg CO_2/yr) or less. These simplified baseline and monitoring methods may increase the attractiveness of small projects.

e. Outskirts of ASF: agroforestry and trees on farms

Low natural carbon densities, slow growing indigenous forest types, high FAD resource need, and small areas available for reforestation within gazetted areas mean that tree planting *outside* ASF will be a necessary part of any project hoping to sell CER credits. The

ASFMT has recognized the need to become involved in activities in forest adjacent areas, called "**the intervention zone**" in the ASF Management Plan (ASFMT, 2002).

Much of the land around ASF is used for small-holder agriculture and is not available for reforestation. However, agricultural yields are low and subsistence crops are often supplemented with **cash crops** such as cashew, mango, and coconut (ASFMT, 2002). These cash crops are *all trees* that do not require a significant harvest of tree biomass to obtain their saleable products. Indigenous trees with **medicinal value** in sustainably harvested bark, fruit, or roots, may also prove lucrative carbon stores despite their slow growth, especially due to their tolerance of local climate conditions. Encouraging planting and maintenance of these trees in local communities, in conjunction with aiding **market access or means of adding value to the produce**, could prove to be an economically viable means of increasing biomass in the area.

Sustainably harvested **fuelwood and timber plantations** on trustlands or **woodlots** on farms could make fuelwood use carbon-neutral or carbon-storing. Fuelwood saving technologies and cooking methods, like fuel-efficient stoves, would help keep demand in line with growth rates. Resource alternatives, resource use efficiency technologies, and sustainable use planning would need to be provided at low cost, if they are to be widely adopted over free forest use. CER investments could be used to cover these costs.

Carbon stock increases from tree planting on farms will be determined by the species planted, tree growth rates, tree species effects on soil pool, harvesting rates for timber or fuel, the number of land holders participating, the number of trees each can grow successfully, and added regeneration benefits from reducing pressure on ASF. Managing and accounting for carbon stocks accrued by separate landholders can pose a challenge. However successful agroforestry carbon offset projects, such as TIST (*Table 1*) have been able to tackle this problem through small group tree planting commitments and group self-monitoring programs.

Some reforestation and alternative energy production projects are already being initiated by local communities through church and school groups. One promising example is the **Muhiri Charcoal Eradication Project (MCEP)** of the Fishers of Men Church. MCEP is currently initiating a voluntary tree-planting project adjacent to Mida Creek in which 50 families have already agreed to plant five indigenous trees and thirty non-indigenous commercial trees each year for eight years (Baya, 2005). Seedlings are bought using donations to the project and distributed at no cost to the families, who receive education about caring for the trees through church meetings. In addition to tree planting MCEP is experimenting with production of non-timber alternatives to charcoal using available materials such as coconut husks, cattle dung, and wood shavings to form burnable briquettes (Baya, 2005). If successful, this is a project that could be extended to other communities, perhaps through CER investments, as an effective carbon emission offset project.

5.4 Potential to attract project funding

ASF and surrounding areas have many **resources and advantages** that make it an attractive location for an investor looking to promote carbon storage projects, such as:

- High levels of biodiversity, adding value for ecologically concerned investors
- Obvious needs for reforestation activities in areas such as Madunguni and county council areas to prevent erosion, protect habitats, and maintain watersheds in this semi-arid area
- A detailed management plan established with stakeholders to help guide project priorities
- A management team with a mandate to foster community involvement in management

- Several organized community groups around the forest which can voice FAD values, needs, and opinions and want to become involved in organized forest management
- Research organizations and other experienced groups on site capable of carrying out and/or facilitating continual forest inventories, nursery building and experiments, and educational activities (eg. KEFRI, Nature Kenya, ASFGA)
- A forest area that is relatively well studied, mapped, and inventoried, reducing effort needed to produce project design documents, baselines, and monitoring plans
- Roads and paths throughout the forest and a major road leading to the forest making the area easily accessible for monitoring and project activities
- Nearby tourism and market centers that make ecotourism activities and sustainably produced forest products easier to promote/sell when creating multiple income streams
- A variety of indigenous and non-indigenous high-value timber, fast growing fuelwood, fruit, and medicinal tree species that have been found to grow successfully in the climate and edaphic conditions in the region giving precedent and potential for increasing agroforestry activities around ASF
- Several alternative income and alternative resource projects in the area (eg. Kipepeo Butterfly Farming project, Muhiri Charcoal Eradication Project) which have been successful and could be expanded upon in to increase their tangeable impacts on

There are some inherent aspects of ASF and surrounding areas that provide **challenges** to initiating an effective carbon storage project in the area, such as:

- Lower maximum achievable biomass densities in indigenous dry forest types compared to wetter forests in increasing indigenous forest cover
- Uncertainty about forest growth rates and potential peak carbon densities
- Slow growing indigenous trees requiring long commitment periods to achieve significant carbon emission offsets through reforestation
- Relatively small uninhabited areas available for reforestation in ASF and Madunguni in relation to their inherent lower carbon densities
- A variety of forest and soil types potentially increasing the research and monitoring efforts needed, such as establishing growth rates and determining the most effective planting regimes.
- Much of the land around ASF is individually farmed and so agroforestry projects would require large groups of consenting parties to make a significant carbon emission offset.
- Proximity to tourism center and market centers creating a market for illegally harvested fuelwood, charcoal, and timber products and increasing the potential for leakage of project benefits if these needs are not addressed
- High forest road accessibility making it easier to illegally harvest and remove relatively large amounts of wood by vehicle.

These would not prohibit the establishment of a carbon storage project, but significant effort would need to be put into planning a project that will address these issues. Such a project will need an investor willing to make a long-term commitment. *While reforestation, afforestation, and improved management are needed in and around ASF and could indeed increase carbon stocks, carbon emission credit investors should not be the only funding source sought to facilitate these activities.*

However, given current efforts to facilitate small-scale carbon offset projects, an active voluntary carbon market with ecologically concerned investors, and precedents being set for small-holder agroforestry carbon projects (*Table 1),* carbon offsets accrued by activities the ASF area, even already initiated projects like Dida PFM, should not go unaccounted. They are valuable and may indeed become tradeable.

6. Recommendations

6.1 Further monitoring and research

Increasing continuous and systematic data collection and processing in and around ASF would be a necessary next step to keeping track of carbon stocks, establishing monitoring protocols for carbon storing activities, submitting baselines and project forecastes, and attracting sponsors. The **carbon densities** and **forest type coverage** estimates found in this study are consistent with previous studies of ASF and literature on dry forests, but estimates of **net growth rates, illegal logging rates, fuelwood offtake,** and **historical carbon losses** used here were relatively speculative for lack of data. Due to widespread historical logging, potential mean carbon densities for ASF forest types were difficult to estimate. Significant relationships between soil types, anthropogenic disturbances, and forest structure, as well as some unexpected relationships between disturbance occurrences and forest stations/guard posts, found in this study deserve more attention.

In light of these concerns there are several ways that future data collection in ASF could better help forest management and also refine carbon stock and stock change detection:

- Continued sampling of **permanent sample plots (PSP)** every 5-10 years
    - Ensure **distribution** of PSPs includes regenerating areas (such as Madunguni, old sawmill areas, and areas with significant illegal logging damage), areas inside and outside the Nature Reserve, and areas under PFM. Plot distribution should also take into account the higher natural heterogeneity of the mixed forest.
    - **Harmonizing methodologies** for all PSPs (recent KEFRI sampling has used two different methods inside and outside the reserve)
    - Mark **individual trees** within PSPs with numbered tags so that growth increments can be collected at the individual tree level over time. This also allows for analysis of growth by species, soil type, slope, climate conditions in preceding years, etc.
    - Engagement of local communities in this process especially through the ongoing **PFM area sampling**
    - Calculate **cost of monitoring effort vs. precision attained** to determine suitable monitoring effort

- Additional sampling of **regenerating areas and natural recruitment** at shorter time intervals to explore factors like seed dispersal and seedling competition with undergrowth.

- Improving forest patrol efforts and increasing the required data collection for **reports of illegal forest product harvesting** including: specific location, species, number of trees cut, and size of trees.

- Expanding of **nursery and on farm data collection and experiments** for both **indigenous and agroforestry species** to determine growth rates, potential for intercropping, and other optimal conditions for reforestation and on-farm planting activities.
    - **Collection of pre-existing knowledge** of growth and suitable conditions of these species from local area residents, other research, and published sources. Significant, helpful data and knowledge exist: eg. reports that *Brachylaena hullensis* regeneration is hindered by seed predation and is more successful in mixed species stands (Omenda, 2000) or that *Brachystegia spiciformis* doesn't grow well in shade while *Manilkara spp* are shade tolerant (Davies, 1992) .
    - **Soil typing and mapping** both within and around ASF.

- Include carbon relevant data collection in future **socioeconomic and resource use surveys.** For example, when determining wood needs for PFM areas, the average mass of a fuelwood headload could be determined in addition to headload demand. When determining agricultural resources of an area, questions about the number and types of trees planted on shambas could be included.

- **Monitor carbon stock changes in PFM areas** like Dida in which regular monitoring is already part of scheduled activity.
    - Ensure data taken in PFM forest surveys is collected and stored in such a way that facilitates carbon density calculations: individual tree dbhs are recorded in plots of known size.

- Improved **data mining, data management, and data storage** for ASF research
    - Creation of **standardized data collection sheets** for sampling PSPs, for PFM area activities, recording illegal harvesting data, with clearly recorded methodologies and metadata (specific meanings of abbreviations, codes, etc)
    - Entry of all ***raw data*** into a **computer database** at the Gede Forest Station, also with standardized methods (species names, column headings, file names, etc) through the creation of standardized spreadsheet templates.
    - **Standardize calculation methodologies** through creation of standard calculation spreadsheet templates (including metadata and instructions) by which data can automatically be transformed. Eg. Spreadsheets for calculating stem densities, basal areas, biomass and carbon densities, growth increments, harvesting rates, etc. can easily be devised.
    - **Mine past surveys and reports** for relevant data and results and including this data in the forest station computer database for easy comparison.
    - Request future **outside researchers** that intend to collect relevant data to enter their data in the database and provide them with appropriate data collection templates to facilitate this.
    - **Ongoing maintenance and public posting of time series and spatial data** showing changes in key factors (biomass, growth figures, illegal cutting detection, etc) over time and distribution of such factors throughout the forest, to help assess ASFMT progress and appropriately target interventions at key locations.

Fortunately the Gede Forest Station and ASFMT is equipped with computers, a GPS, GIS software, and staff members capable of carrying out these functions or training others to do so. In addition, local schools, university students, volunteers, and ecotourist groups could be engaged to help conduct the data collection or data management. While initiating a comprehensive database maybe time consuming it is likely to save time and investment in the future. This type of data and data management are needed for the monitoring of increased carbon stocks, but would also be invaluable in increasing the efficiency of sustainably managing ASF.

6.2 Project planning

In the short term, it appears that the greatest potential for a funded carbon emissions offset forestry project in and around ASF lie in rehabilitating Madunguni Forest and fostering agroforestry in forest adjacent zones. Indeed these are the only activities that could receive CDM funding. Due to low carbon denisties these activities are most likely to be small-scale AR projects rather than large projects, meaning few saleable CER credits, but simplier monitoring requirements. It would be worthwhile submitting plans for such activities to various carbon investors (*Appendix E*) and NEMA amongst other donor sources. Improved management and PFM would also have a marked effect on carbon stocks over a longer time scale. Efficient and continuous monitoring of the effects of management and PFM activities is warranted, however, as it will provide useful management data for other purposes and carbon credits from these activities are tradeable on voluntary markets and could be saleable in future CDM commitment periods.

With or without an investor interested in CERS, investing in some of the above recommendations should enhance the carbon stock of ASF and surrounding areas, increasing Kenya’s carbon sinks and having positive influences on the global and local climate, in addition to the sundry other benefits of increased forest quality and agroforestry. These activities would also reduce future expenditures for Kenya as developing nations may also have to closely monitor their GHG emissions. The costs of carbon emission mitigation will increase as time passes if forest continues to be exploited and cleared. Rehabilitation is more costly and requires much more time and effort than forest loss prevention.