Carbon Storage and Sequestration Analysis for the eThekwini Environmental Services Management Plan Open Space System

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Summary

Global climate change will be one of the most significant challenges to sustainable development worldwide, and the eThekwini Municipality will be no exception. Atmospheric concentrations of heat-trapping greenhouse gases (GHGs) have increased rapidly since the Industrial Revolution due to human activities, primarily fossil fuel burning and land cover change. This increase has been associated with the increase in global temperatures and local changes in weather patterns (IPCCC, 2001). South Africa is a significant contributor to global GHG production, being ranked the fourteenth greatest emitting nation in the world (World Resource Institute, 2006), but will be also faced with significant challenges from increased temperatures, decreased water availability, and sea level rise expected to result from climate change.

In 2004, the eThekwini Municipality commissioned a study of localized climate change impacts to better understand the possible consequences for the planning and development of the city of Durban (CSIR, 2006). Likely negative impacts include: increased health problems due to heat stress and increased malaria ranges; declining agricultural production, dam recharge, and water availability due to increased temperatures coupled with more concentrated rainfall patterns; loss of biodiversity due to changed temperature and rainfall; and loss of key economic infrastructure to sea level rise. It is clear the eThekwini municipality needs to take action to both mitigate and adapt to impending climactic change.

The eThekwini Environmental Services Management Plan (EESMP), Durban's open space system, provides the municipality with both adaptation and mitigation services. The EESMP area spans 64,037 ha and contains a wide variety of ecosystems including, grasslands, wetlands, woodlands, and forests both in public reserves and private landholdings. These ecosystems store carbon in their vegetation and soils that could otherwise be released as carbon dioxide (CO_2), a greenhouse gas, if the land was converted to urban or agricultural cover. In addition to storing carbon, these ecosystems provide many other ecosystem services, such as flood water attenuation and urban cooling effects, that will become crucial in adapting to climate change impacts, such as changed rainfall patterns and increased temperatures.

The eThekwini Environmental Management Department (EMD) assessed the carbon storage capacity of this open space system to determine how much carbon the EESMP stores and identify feasible opportunities to increase the carbon uptake of the system. In addition, these opportunities were assessed for their potential to attract added funding through international carbon markets. As a result of global concern about climate change and the acknowledgement of the more industrialized nations that they have contributed the most to GHG emissions, international carbon markets have developed as part of efforts to decrease net GHG emissions. One of the tools available in these markets is for carbon emitting nations or industries to fund projects that either increase ecosystem carbon storage or reduce GHG emissions in the global south. The United Nations formalized these efforts through the Clean Development Mechanism (CDM) of the Kyoto Protocol, but other trading of carbon credits occurs on the voluntary market. The voluntary market consists of organizations, companies, or individuals that fund projects or buy carbon credits although they have no governmental directive to reduce emissions.

The carbon stock of the EESMP was estimated by field sampling of both vegetation and soils in all the main vegetative cover types in the open space system. By sampling a series of plots in each cover type, an average carbon density (amount of carbon stored per unit area) was estimated for each type and was multiplied by the area of that vegetation type to determine total stocks. The Century ecosystem model was used to estimate carbon sequestration rates under predicted climactic changes for both disturbed and undisturbed cover classes. It was found that the EESMP in 2005 had a store of 6.6±0.2 million tons of

carbon (Mt C) equivalent to 24.3±0.9 million tons of carbon dioxide (Mt CO_2), roughly equal to the annual emissions of 3 million South Africans (7.82 t CO_2/cap; World Resources Institute, 2006). The EESMP conservatively sequesters 8,400-9,800 tons of carbon per annum (tC/yr), which is 31,000-36,000 tons CO_2/yr, equivalent the annual emissions of 4,600 South Africans. Predicted climactic changes may slightly increase sequestration potential.

Carbon densities found in the inventory agreed well with the published literature. It was found that forests and wetlands had significantly greater carbon densities than other cover classes, but were fairly well protected by zoning and environmental legislation. Fifty-eight percent of the municipal carbon stocks, however, were on land that could potentially be developed, primarily due to the lack of protection of high carbon density Dry Valley Thicket/Broadleaf Woodland. Protection of these ecosystems through zoning and environmental servitudes, and reducing carbon losses in developments through environmental management plans, could help maintain carbon stocks. While these activities are part of the core business of the EMD, they may be augmented by carbon funding (through voluntary markets) and by increased climate change awareness amongst development stakeholders.

Alien infested and disturbed ecosystems provide opportunities to increase the carbon storage of the EESMP through rehabilitation activities. These classes were found to have significantly lower vegetation and/or soil carbon stocks that other cover types growing on similar soils and climactic conditions. Efforts to convert these cover types to the appropriate intact indigenous cover would increase carbon storage, result in job creation, and, where activities involved tree planting, could attract carbon offset funding from either CDM or voluntary markets. In peri-urban and rural areas of the municipality that rely on resources such as fuelwood and building material from the open space system, sustainable harvesting plans and woodlots could both increase carbon storage and maintain valuable resources.

The EESMP carbon stock and rate of sequestration are small in comparison to the GHG emissions estimated for the municipality in its *State of Energy Report* (EThekwini Municipality, 2006). Nevertheless, if the EESMP is protected, it is likely that land cover change will not be a significant source of GHG emissions in the municipality, and the rehabilitation of ecosystems within the EESMP will improve the role of the open space system as a carbon sink.

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Abbreviations

AGB	Aboveground biomass – mass of plant organic matter occurring above soil surface, not roots
BGB	Belowground biomass – dry root mass, mass of plant organic matter occurring below soil surface
CDM	Clean 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
EESMP	EThekwini Environmental Services Management Plan, a GIS based system of both protected and unprotected, public and private, critical open space remaining throughout eThekwini municipality
EMA	EThekwini Municipal area (2,297 km^2)
EMD	Environmental Management Department of the eThekwini Municipality's Development Planning and Management Unit
DEAT	Department of Environmental Affairs and Tourism (National)
Dbh	diameter at breast height, tree diameter taken at 1.3 m from the ground
DME	Department of Minerals and Energy, South Africa's Designated National Authority for the Clean Development Mechanism
DNA	Designated National Authority for the Clean Development Mechanism
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
ICLEI	International Council for Local Environmental Initiatives (now known as ICLEI - Local Governments for Sustainability)
IDP	Integrated Development Plan, development goals document for eThekwini Municipality
IPCC	Intergovernmental Panel on Climate Change, an international panel of scientists established under the UNFCCC
IUCN	World Conservation Union
KZN	The province of KwaZulu-Natal
LOI	Loss on ignition – a procedure to measure carbon in soils by combusting samples and measuring the mass lost assuming this constitutes the amount of burnable organic material, hence carbon, in the sample
MAP	Mean annual precipitation (mm)

MAT	Mean annual temperature (^oC)
NEMA	National Environmental Management Act of South Africa
NEES	National Energy Efficiency Strategy
NR	Nature Reserve
UNFCCC	United Nations Framework Convention on Climate Change

Units and conversions

CO_2	Carbon dioxide gas
C	Carbon – usually carbon as a solid in biomass (organic matter)
kg	Kilogram
t	Ton = 1,000 kg
Mt	Megaton or Million tons = 1,000,000 t
ha	Hectare = 10,000 m^2 (square meters)

1 Introduction

Climate change, or climate disruption, is one of the foremost threats to sustaining biodiversity, ecosystem services, and human well being worldwide. Global climate disruption is driven by the build-up of **greenhouse gases (GHGs)** that trap heat in earth's atmosphere. This build-up has been primarily due to anthropogenic fossil fuel burning and land cover change (IPCC, 2001). It is predicted that of all regions of the world, Sub-Saharan Africa will be most severely affected with the highest predicted mortality rates linked to climate change impacts such as crop failures, increased disease ranges, and heat waves (Patz et al., 2005). South Africa is highly vulnerable to various climate change impacts because it is:

- the third most biodiverse country in the world (World Conservation Monitoring Centre, 1992)
- largely semi-arid and suffering from freshwater scarcity
- depends heavily on coastal infrastructure and economic activity
- dealing with issues of widespread disease and poverty.

At the same time, South Africa makes a significant contribution to the problem: it is ranked fourteenth in the world for annual carbon emissions, the primary GHG emitted globally (World Resources Institute, 2006). To address sustainable development in South Africa, the nation must address both the causes and effects of climate change.

The eThekwini Municipality has made a strong commitment to sustainable development. The city accepted the Local Agenda 21 mandate, an internationally derived action plan for socially, environmentally, and economically sustainable development, in 1994 and has continued this sustainability emphasis in its Integrated Development Plan (IDP). To attain sustainability, the municipality must address the causes and impacts of climate change and loss of ecosystems and their services. EThekwini Municipality's Environmental Management Department (EMD) has taken several steps in this direction through the establishment of the **eThekwini Environmental Services Management Plan (EESMP)** and participation in the ICLEI Cities for Climate Protection (CCP) program.

The eThekwini Municipality, as part of its Climate Protection Program, is working towards climate change mitigation and adaptation, and land cover management could be a key tool in this effort. Conversion of natural ecosystems, typically rich in solid carbon stored as organic matter, to developed urban or agricultural landscapes results in the release of gaseous carbon dioxide, a GHG (Houghton, 1997). Concerns about climate change and the loss of natural ecosystems have motivated scientific efforts to quantify the roles of ecosystems in the global carbon cycle, and political efforts to make ecosystem preservation more socio-economically attractive (Brown, 1997; Houghton, 1997; Watson et al., 2000). This study aims to quantify the amount of carbon stored in the ecosystems represented in the open space system of the eThekwini Municipality and to assess opportunities to maintain or increase this storage as a means to both mitigate climate change and preserve ecosystem integrity.

The eThekwini Municipal Area (EMA) of KwaZulu-Natal, on the country's east coast, is naturally rich in biodiversity, but must also support a dense, diverse, growing human population and a variety of nationally important economic activities. Roughly 27% of the EMA has been designated as an open space system within the context of the EESMP. This area contains 97 km of coastline, 18 river catchments, and seven general vegetation types that support at least 177 terrestrial IUCN red data species (eThekwini Municipality, 2005). It supplies sundry ecosystem services to the 3 million EMA residents, such as water and air supply and purification; erosion and flooding prevention; food, fuel, and medicinal resources; and tourism and recreational areas, the value of which was estimated to be R 3.1 billion per annum in 2002 (eThekwini Municipality, 2005). This open space system also serves to store carbon and mitigate the effects of climate change. However ecosystem area loss and degradation, compounded by climate change impacts such as altered temperatures, precipitation regimes, and sea level, will threaten its capacity to deliver all these services.

The biodiversity value and ecosystem services of eThekwini's natural resource base have been taken into account in the design of the current EESMP; however, its role as a dynamic carbon store, providing not only a local, but a global ecosystem service in mitigating climate change, has not been quantified. This study uses field sampling of key terrestrial land cover types in the municipality to estimate the carbon stock of the open space system and assess the potential to increase carbon storage. It is possible that carbon sequestration activities could attract international, and perhaps internal, funding to aid restoration and management efforts. The results of this study can also be compared to municipal GHG emissions to assess the net emission and climatic influence of eThekwini Municipality.

1.1 *The Greenhouse effect and land cover change*

Since the Industrial Revolution, the concentration of carbon dioxide (**CO_2**) in the earth's atmosphere has steadily increased at a rate faster than any changes seen in the past 650 thousand years (Siegenthaler, 2005). Human activities that produce atmospheric carbon include:

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

Because CO_2 traps heat in the earth's atmosphere like a blanket (the **greenhouse effect**) significant increases in atmospheric carbon impact the earth's climate. Several other gases, such as methane (CH_4) and nitrous oxide (N_2O), also act as **greenhouse gases (GHGs)**. 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 atmospheric GHG concentrations will increase global average temperatures, leading to:

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

Increased temperature, increased extreme weather event frequency, and increased rainfall variability have already been observed in recent years (IPCC, 2001). 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)

The *Climactic Future for Durban* report was compiled by the CSIR in conjunction with the eThekwini Municipality in 2006 to forecast some of the local impacts of climate change on the EMA with a view to developing a mitigation and adaptation strategy. Just a few impacts are mentioned here, but overall climate change is predicted to pose significant challenges to eThekwini's social, economic, and ecological sustainable development goals

(CSIR, 2006). Average rainfall in the EMA is predicted to increase slightly but its distribution will change with longer dry periods and shorter wet periods with more intense rainfall. This will affect agriculture, increase erosion, degrade river habitat, and decrease recharge of major dams from which most of the municipality receives water. Predicted sea level rise and storms will affect the EMA's unique remaining coastal vegetation and the infrastructure, residences, key industries, and economic activity of the central business district, the harbor, and South Basin area.

While the majority of the recent increase in global atmospheric carbon can be attributed to fossil fuel burning, it was estimated that **land-use change**, primarily the loss of forest cover, has been responsible for 20-30% of the net increase (Houghton, 1997). Globally, in 1999, 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). Plants remove carbon dioxide from the atmosphere (**carbon sequestration**) in photosynthesis and use this carbon to build their body structures (their biomass) during photosynthesis. As a result, roughly 50% of a plant's dry biomass is comprised of carbon.

Ecosystem carbon is **stored** terrestrially in living woody and herbaceous biomass, dead wood and leaf litter, and soil organic matter. Some of this carbon is released back into the atmosphere when litter and soil organic matter decomposes or biomass is burned. The amount of carbon stored in an ecosystem depends upon the balance between plant growth rates and decomposition rates. In addition to *storing* carbon, ecosystems may also act as **carbon 'sinks'** if the rate of carbon sequestration from plant growth exceeds the rate by which carbon is returned to the atmosphere through natural decomposition and/or biomass burning. Forests, with their high density of woody, high biomass vegetation and soil enriching litter production, typically have higher **carbon densities** (carbon stored per unit area) than other vegetation cover types. Savannas, grasslands, and wetlands can, however, store significant amounts of carbon in their soils if soil organic matter is not rapidly broken down. This is often the case for wetlands as the inundated soils lack oxygen needed for decomposition.

As ecosystems are converted to less carbon rich land cover types, such as plowed agricultural fields, residential, or urban areas, much of the carbon stored in biomass and soil is released into the atmosphere. Preventing further deforestation and encouraging regeneration not only preserves biodiversity and local ecosystem services, but can also mitigate global climate change. In addition, **reforestation** and **afforestation** (forest growth in an area not previously forested) activities can attract funds for sustainable development from emerging international carbon emission offset markets. Although net global GHG emissions can not be addressed without addressing fuel consumption, managing land cover change provides a significant opportunity for climate change mitigation coupled with a myriad of other ecosystem conservation benefits.

1.2 International agreements and carbon emissions offset trading

In an effort to mitigate global climate change, 189 nations, including South Africa, have signed the **United Nations Framework Convention on Climate Change (UNFCCC)** drafted in 1992 (UNFCCC, 2006). **Party nations**, those which have *ratified* (accepted responsibility to implement) the convention, agreed to produce **national GHG emissions inventories** that assess contributions from industrial and agricultural sectors, transportation, energy production, land cover change, and forest losses and growth within their borders. Knowledge of these trends is used to design climate models that forecast future changes and to identify key areas for emissions reductions and sequestration.

The UNFCCC acknowledges that industrialized nations hold the greatest responsibility for emitting GHGs, while the developing world will suffer the brunt of the consequences (UNFCCC, 2006). As a result, 41 listed **industrialized nations (Annex I)** were deemed responsible for reducing their collective 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 on 16th February 2005, binding industrialized party nations to reduce their carbon emissions by the end of 2012 to levels below their estimated emissions for the year 1990.

Atmospheric GHGs have global climactic effects regardless of where they are released, and the same can be said for emissions reductions or sequestration. In light of this, the Kyoto Protocol includes several *'flexibility mechanisms'* permitting industrialized nations to reduce global GHG concentrations by investing in emission reduction activities in other countries. This can be more economically efficient than instituting emission reduction measures in the developed nation. However, to avoid industrialized nations completely ignoring the sources of their own emissions, nations must achieve the bulk of their emission reductions within their own borders (UNFCCC, 2006).

One of these flexibility mechanisms, known as the **Clean Development Mechanism (CDM)**, Kyoto Protocol Article 12 (party approved in 2000 and refined in the 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 can foster technology transfer. Such projects include the establishment of:

- reforestation activities
- productive plantations or agro-forestry systems with sustainable harvesting rates
- energy efficiency improvements
- cleaner/renewable energy production and industrial manufacturing methods

These activities qualify for CERs if they produce measurable net GHG emissions reductions that would not have otherwise occurred without the CER investment (**additionality requirement**). Projects must also account for and minimize **'leakage'**, that is any added GHG emissions that may occur outside the project area as a result of project activity. Industrialized nations or institutions that have GHG reduction quotas can fund and develop projects directly or they can simply purchase CERs from other bodies, such as private companies, aid agencies, development banks, NGOs or host nation government organizations, that have provided project funding and registered the emission reductions.

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. It receives guidance from the **Conference of the Parties (COP)** that consists of all nations that have ratified the Kyoto Protocol. The most recent meeting of the COP occurred in Nairobi in November 2006. To participate in the CDM, nations must:

- ratify the Kyoto Protocol
- show that participation is voluntary,
- establish a **Designated National Authority (DNA)** to facilitate, evaluate, and approve CDM projects as beneficial to the host nation.

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**, a **carbon baseline** (*predicted carbon storage and emissions without the project*) must be established specifically for the project area. A project predicted to feasibly reduce atmospheric GHGs must then be approved by the host nation's CDM DNA and be evaluated by an independent party for approval by the Executive Board. Internal GHG monitoring and subsequent independent review will be required for the executive board to issue CERs.

To be approved by the host nation's DNA, the project must satisfy social, economic, and environmental sustainability criteria, which are to be transparently established by the host. In addition project developers are required to request public comment on their project and demonstrate how they have dealt with stakeholder concerns. The importance of this is clearly demonstrated in two pre-CDM carbon-offset forestry projects in Uganda. One project established pine and eucalyptus plantations on marginal agricultural lands, evicting 8,000 project area inhabitants without due compensation while also lacking firm evidence of substantial carbon benefits (Eraker, 2000 a; Eraker, 2000 b; World Rainforest Movement, 2000). The result was arson and felling by dissatisfied local residents, public criticism from NGOs, an unfavorable carbon storage review, investor withdrawal, and project discontinuation (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 Mt C and employing local residents in project management, monitoring, and planting (Watson et al., 2000; World Resources Institute, 2002).

In addition to the Kyoto market for CERs, there is also a **voluntary carbon trading market** for bodies such as aid agencies, NGOs, environmentally conscious companies, and even individuals, interested in funding carbon emission reduction or carbon storing projects. The United States, which produces over 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 several American industries have funded international forestry projects to counteract their emissions on voluntary markets (World Resources Institute, 2002). The principles of additionality and leakage accounting apply in the voluntary market, but registration and approval procedures are generally simpler and less costly. Buyers and hosts can also require that a project go through the nation's DNA or is otherwise certified for sustainability. For example, the Climate, Community, & Biodiversity Alliance (CCBA) provides sustainability standards for voluntary certification (CCBA 2005).

The CDM has been active since the Kyoto Protocol came into force in 2005 and since then over 240 projects have been registered by the Executive Board and it is predicted that over one billion tons of carbon emissions will be offset by CDM projects by 2012 (Climate Change Secretariat UNFCCC 2006). Although the CDM has seen little movement on forestry and land cover based projects, the voluntary market for them has been very active with over 150 bilateral forestry carbon emissions offset projects had been developed by the year 2000 (Bass et al., 2000). 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. Examples of funded land cover carbon offset projects are listed in *Appendix A*.

1.3 *National and local government action*

South Africa has acknowledged the threats of climate change and has taken some initial steps towards mitigation and adaptation. The South African government ratified the UNFCCC in 1997 and the Kyoto Protocol in 2002. The **Department of Environmental Affairs and Tourism (DEAT)** submitted the first communication to the UNFCCC in 2000, containing estimated countrywide GHG emissions and sequestration for 1990 and 1994. Following this, DEAT prepared a *National Climate Change Strategy* in 2004 consisting of a general government action plan to integrate and capacitate various departments to engage in adaptation, mitigation, education, and research activities and to prepare a national mechanism for carbon trading (DEAT 2004). Although South Africa is ranked fourteenth in the world for total carbon emissions, it is considered to be a developing nation by the UNFCCC and is not Kyoto mandated to reduce its GHG production in the first reduction commitment period (2008-2012). It is possible that South Africa could be assigned GHG reduction targets in post-2012. At the moment however, South Africa can receive international funds for any emission reductions it makes through the CDM or voluntary market.

The **Department of Minerals and Energy (DME)** was established as the DNA in 2004 and has established a project review and approval process with a set sustainable development guidelines projects must comply with to receive host nation approval. By December 2006 five CDM projects approved by the DME had been registered by the CDM Executive Board including one in eThekwini. These are the:

- Kuyasa Low-cost Urban Housing Energy Upgrade, in which solar panels, solar water heaters, and energy efficient light bulbs were used in low cost housing near Cape Town
- Lawley Fuel-Switch Project, in which Corobrik Ltd.'s Lawley brickworks will switch from coal and petrol to cleaner burning natural gas.
- Rosslyn Brewery Fuel-Switch Project, in which South African Breweries will switch from coal to natural gas and biogas to power their Rosslyn facility.
- Bethlehem Hydro Project, in which Bethlehem Hydro Ltd will develop a 4 MW hydrological dam that will operate as an independent power plant.
- Durban Landfill-gas-to-electricity project – Mariannhill and La Mercy Landfills, in which gases produced in these landfills will be harvested and used to produce 10 MW of electricity and reduce carbon emissions by a predicted 68,800 tons carbon dioxide per annum.

Up to this point the focus of the CDM in South Africa has been energy related projects, however the DME is currently working to define its modalities for reviewing forestry based projects.

On a national level, outside of CDM participation, few tangible incentives or directives are given to reduce South Africa's emissions. On a local government level, eleven South African cities have participated in the **Cities for Climate Protection program (CCP)**, a campaign launched in South Africa in 2001 by **ICLEI, Local Governments for Sustainability** (formerly International Council for Local Environmental Initiative). EThekwini Municipality is one of these cities. Participating cities must inventory their energy use and GHG emissions in city operations, forecast emissions for 10-20 years, set an emissions reduction/avoidance goal, develop and implement an action plan to achieve the goal, monitor and verify the progress. The eThekwini Municipality has completed an inventory of GHG emissions in municipal operations (EThekwini Municipality 2003), and is embarking on an inventory for the entire EMA. The municipality is further committed to address climate change in its operations because it has accepted the sustainable development guidelines of Agenda 21 (from the World Summit of Sustainable Development, 1992) as a corporate responsibility.

1.4 Land cover based carbon offset opportunities for eThekwini Municipality

The **eThekwini Environmental Management Department (EMD)**, in its efforts to conserve the remaining biodiversity in the municipality, has already made progress in avoiding carbon emissions associated with ecosystem destruction. In 1999/2000 the EMD received a council approval for the first iteration of the **eThekwini Environmental Services Management Plan (EESMP)**. The EESMP was established through a consultative prioritization of areas critical to maintaining ecological viability and sustaining ecological services which was captured in a Geographic Information System (GIS). This resulted in a 64,037 ha open space system containing a variety of land cover types, both protected and unprotected, under both public and private ownership.

Areas protected as reserves or conservancies or areas unsuitable for building due to steep slopes or flooding are regarded as relatively secure, but for other privately owned land included in the EESMP several tools are employed to preserve the integrity of the open space system. These mechanisms include education and consultation with developers and landholders, requesting **environmental servitudes** with a property rates reduction for environmentally sensitive portions of a landholding, **environmental management plans (EMPs)** for developments, and, in special cases, outright purchase of vulnerable land.

Durban’s open space system includes forests, woodlands, grasslands, and wetlands that store carbon and may provide opportunities for increased sequestration and potential carbon trading. **Afforestation and reforestation** (**A/R**) of degraded areas can sequester carbon from the atmosphere and store it in tree biomass. During the first emissions reductions commitment period of the Kyoto Protocol (2008-2012), A/R activities are the only land use projects for which industrialized nations can receive CERs from the CDM. To avoid creating incentives to clear and then reforest, CERs will only be issued for reforestation of areas cleared pre-1990. **Deforestation prevention and improved land management** do offset carbon emissions but are not currently accredited in the CDM. However, possibilities for such projects to receive carbon funding exist in the voluntary carbon market and in future commitment periods of Kyoto after 2012.

Substantial opportunities exist to reforest Africa’s large areas of degraded land and promote sustainable energy production as African nations develop. However, due to a lack of capacity and information, a lack of funding for initial project development and legal mechanisms to process projects, and insecure investment environments, Africa has not been a significant player in the carbon market to date. Only 5 of the 242 CDM projects registered by July 2006 were in Africa while there were 124 in Latin America. One of the topics for the November COP meeting in Nairobi was how to better use the CDM to promote sustainable development in Africa (UNFCCC 2006).

A large amount of information is needed to initiate a carbon project, particularly for a land cover based initiative. A **carbon baseline** and **monitoring program** need to be established for a project area with third party monitoring from a certified body. For A/R projects this requires rigorous forest inventories. Compared to the Neotropics, 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).

In Africa, South Africa, and in particular the eThekwini Municipality, is well poised to initiate land use projects to sequester carbon and opportunities exist to attract carbon trading funds. South Africa has established its DNA and methodology for project approval and has succeeded in registering projects with Executive Board. In addition, there are two CDM executive certified third-party project auditors (called Designated Operational Entities, DOEs) with South African branches: PricewaterhouseCoopers-South Africa and Det Norske Veritas Certification Ltd, thereby reducing project transaction costs. Foreign reviews of the carbon market have given South Africa good ratings for its opportunities and investment environment, better than any other African nation (BFAI 2006). While much of South Africa is arid or semi-arid with grassland and savanna as the natural vegetation type, the wetter climate of the east coast has facilitated indigenous forest growth and would allow for A/R activities. The eThekwini Municipality has already mapped vegetation cover and keeps updated aerial photographs and ecosystem maps on GIS, which significantly reduces the effort required to measure and monitor carbon storage and land use change.

In theory, several opportunities exist for eThekwini Municipality to maintain and increase carbon sequestration, and a carbon storage inventory will help assess the possibilities. The activities of the EMD in trying to secure open space areas that would otherwise be developed are one example. Avoided deforestation is not currently a CDM activity but may be considered post-2012 and can produce credits on the voluntary market. Because this work is already ongoing, it would not pass the additionality requirement for trading, however if additional funding would allow for activities to be expanded beyond current levels, trading would be a possibility. It may be possible for localized, detailed awareness of the carbon costs of clearing land, or perhaps carbon funding, to incentivize landholders to place environmental servitudes on their properties.

Habitat rehabilitation, agroforestry, and/or sustainable woodlots for community needs in peri-urban/rural areas could qualify as CER producing A/R activities and/or voluntary market projects. To encourage tree planting on small available areas or by groups of individual landholders, the CDM board has come up with simplified project procedures and activity bundling options for **small-scale afforestation or reforestation (SSC-A/R) projects** that store 8,000 t CO_2 or less per year through establishment of tree cover on land that had grassland or cropland as its starting condition. These methods simplify baseline calculations by assuming carbon stocks would not change from the pre-project condition in the absence of the project activity rather than requiring detailed future growth and management scenarios. Only changes in woody biomass (above and belowground) are considered and need to be monitored in permanent plots in 5 year intervals, although soil, litter, and herbaceous vegetation stocks may change. Leakage calculations are unneeded if no households or crop land is displaced in the project. Due to the limited size and patchwork nature of the open space system, it is likely that such efforts would take place as several SSC-A/R projects.

2 Methods

2.1 Study site and land cover classification

EThekwini Municipality in the Province of KwaZulu-Natal is located on the eastern seaboard of South Africa (2,2297 km^2 area; 29.5-30.3°S, 30.6-31.2°E). Altitudes in the EMA range from sea level at the coast to 870m inland. The mean annual temperature (MAT) for the EMA is 21°C. Precipitation varies throughout the EMA, influenced by altitude, terrain, and distance from the ocean, with mean annual precipitation (MAP) ranging from 500 to 1000mm averaging at 930mm. The open space system, or the EESMP, consists of 64,037 ha containing a variety of forest, woodland, grassland, and wetland types (*Figure 1*, *Table 1*). Soils in the EMA are generally sandy or silty with the majority forming on Natal Group Sandstone or Granite (*Appendix B*), with finer alluvial soils along drainage lines.

The land cover mapping of the EESMP was chosen as the most appropriate land cover classification for this study. The EESMP GIS map was developed using visual analyses and ground-truthing of 1: 5000 aerial photography from 2000 (EThekwini Municipality, 2001). Its boundary lines are subject to ongoing refinement by the EMD. Alternate vegetation classifications and maps have been created by the South African National Botanical Institute (SANBI) and by eZemvelo KZN Wildlife (provincial government); however, the coarse scale of these maps and the fact that they do not include the more impacted cover types such as feral plantations or alien species dominated woodlands, made them impractical guides for sampling and carbon budget calculations.

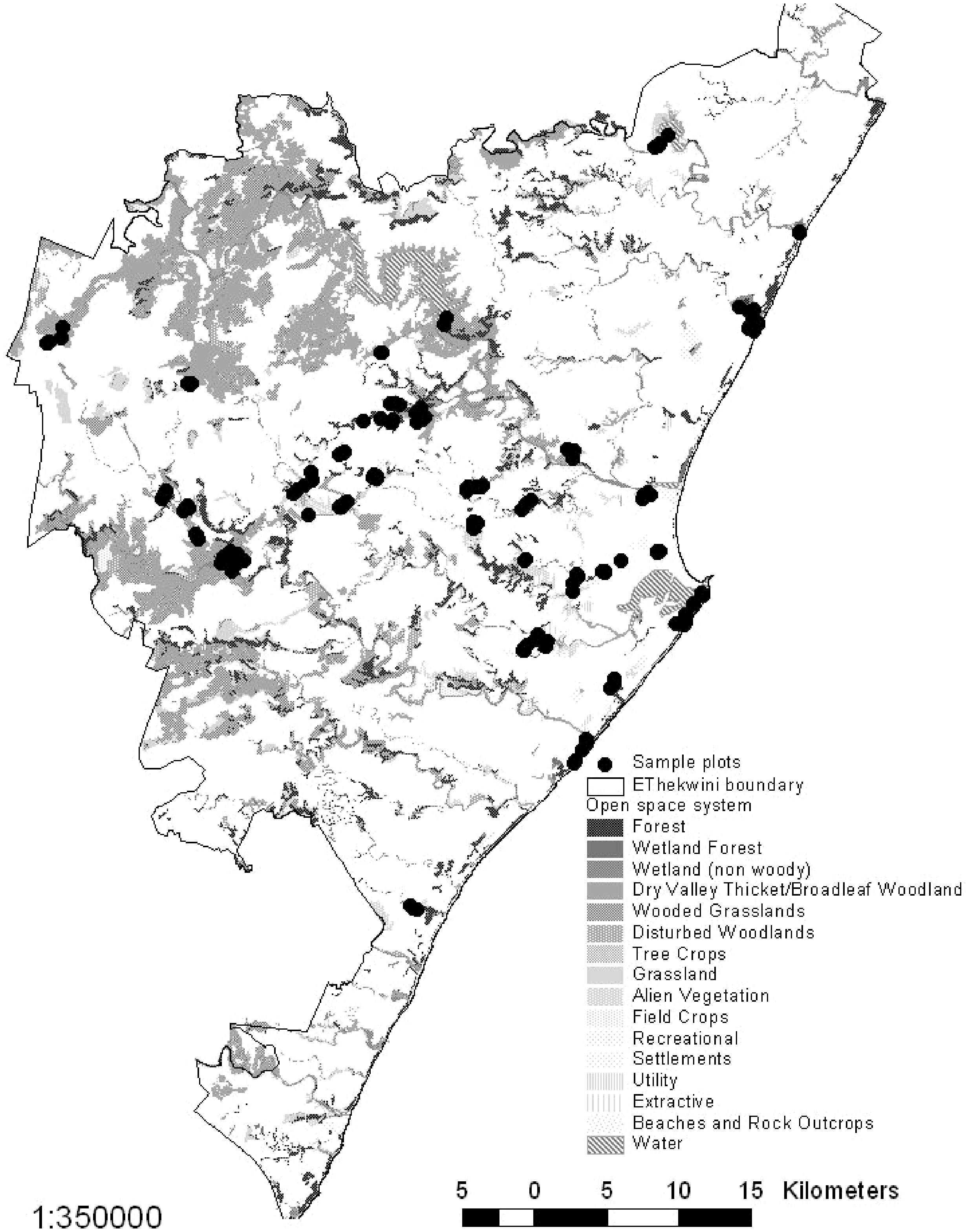
Mean carbon densities (carbon stored per unit area) were estimated from sample plots for various cover types. Sampling sites were picked to get a spatial spread throughout the EMA while sample plots were located randomly within each site. Sampling intensity, that is, the number of plots sampled, in various land cover classes (*Table 1*) was determined by their coverage in the EMA and their predicted carbon density and spatial heterogeneity. For example, intact forests were assumed to have greater carbon densities and more heterogeneous storage than grasslands, and therefore more sample plots were done in forest classes. Intact ecosystems were prioritized as these were assumed to have greater carbon densities and represent the end point carbon densities of possible restoration efforts. These classes were sampled in 10 plots each after which mean carbon densities and standard errors were calculated. Those with the highest carbon standard errors were then allocated the remaining sampling days with those having the highest carbon densities being receiving priority. While attempts were made to minimize the standard error of mean carbon density estimates through appropriate sampling intensity, sampling was also limited by the time and resources available.

Not all cover types in the open space system were sampled, while others received minimal sampling. Cover classes defined by disturbance, such as 'Disturbed Woodland' and 'Transitional Forest,' were known to be very heterogeneous by definition as the levels and timeframes of disturbance vary significantly from site to site. As a result a great sampling effort would be needed to establish representative carbon density means for these types and thus they were sampled cursorily to give rough 'order of magnitude' figures. If these areas were to be rehabilitated, site specific monitoring would be needed to assess carbon stock change for the project area. Cover classes with insignificant coverage were not sampled and carbon densities were approximated from other relevant sampled classes or literature as available.

Table 1 Cover class distribution and sampling intensity in eThekwini Municipality's open space

EESMP General Description *(Detailed subclasses)*	**Area (ha)**	**% of Open Space**	**Plots (n)**	**Sites sampled**
Dry Valley Thicket/Broadleaf Woodland	18,610	29.1%	17	Inanda Valley area, Krantzkloof NR, Shongweni Valley & NR, Summerveld, Thornridge farm
Wooded Grasslands	11,393	17.8%	30	
Unspecified	*7,226*	*11.3%*	*9*	Summerveld, Thornridge farm
Coastal Bushclump Grassland	*3,785*	*5.9%*	*13*	New Germany NR, Stainbank NR
Acacia Savanna	*362*	*0.6%*	*8*	Fosaville
Protea Woodland	*12*	*0.0%*		(small area, approximate using other classes)
Faurea Woodland	*8*	*0.0%*		(small area, approximate using other classes)
Forest	10,646	16.6%	66	
Coastal Scarp Forest	*4,683*	*7.3%*	*20*	Giba Gorge, Krantzkloof NR, Palmiet NR, Paradise Valley NR, Shongweni NR, Tanglewood
Transitional Forest	*3,072*	*4.8%*	*9*	Giba Gorge area, Ipithi NR, Paradise Valley, SAPREF dune
Coastal Lowland Forest	*989*	*1.5%*	*20*	Burman Bush, Hawaan Forest, Stainbank NR, Pigeon Valley, Wentworth Forest
Dune Scrub and Forest	*925*	*1.4%*	*17*	Bluff military base, SAPREF dune, Umdloti, Umhlanga
Riverine Forest	*833*	*1.3%*		(approximate using scarp & lowland forest)
Unspecified	*143*	*0.2%*		(small area, approximate using other classes)
Wetland (non woody)	5,706	8.9%	13	
Floodplains	*4,988*	*7.8%*		(approximate using freshwater wetland)
Freshwater Wetland	*621*	*1.0%*	*6*	Roosfontein NR
Estuarine Wetland	*96*	*0.2%*	*7*	Umdloti estuary
Alien Vegetation	3,787	5.9%	17	
Alien Thicket	*1,964*	*3.1%*	*4*	Hazelmere dam area
Alien Woodland	*1,169*	*1.8%*	*5*	Cato Manor, Giba Gorge area
Feral Plantation	*653*	*1.0%*	*8*	New Germany NR, Tollgate plantation
Grassland	2,855	4.5%	15	
Secondary Grassland	*1,889*	*3.0%*	*4*	Stainbank NR, Drummond
Primary Grassland	*920*	*1.4%*	*11*	Drummond, Krantzkloof NR
Not Applicable	*46*	*0.1%*		(approximate using other grassland classes)
Disturbed Woodlands	2,833	4.4%	7	Little Amanzimtoti area, Summerveld
Recreational *(parks, golf & sports)*	1,710	2.7%	3	Old Fort Park
Wetland Forest	208	0.3%	5	
Swamp Forest	*85*	*0.13%*	*3*	Alfred Park NR
Mangrove Forest	*56*	*0.09%*		(approx from literature: Umgeni estuary)
Not Applicable	*43*	*0.07%*		(approximate using other classes)
Barringtonia racemosa Forest	*24*	*0.04%*	*2*	Umdloti estuary
Hibiscus tiliaceus Forest	*0.4*	*0.001%*		(small area, approximate using other classes)
Settlements *(sparsely settled rural)*	903	1.4%	N/A	(approximated from woodland classes)
Field Crops	741	1.2%	N/A	(approximated from literature)
Tree Crops	14	0.02%	N/A	(approximated from literature)
Utility *(cemetery, road reserve, etc)*	289	0.5%	N/A	(approximated using grassland & park)
Water	3,099	4.8%	N/A	(not considered a carbon store)
Beaches and Rock Outcrops	1,040	1.6%	N/A	(not considered a carbon store)
Extractive *(rock & sand quarry)*	203	0.3%	N/A	(not considered a carbon store)
TOTAL	64,037		173	

Figure 1 Locations of sampled plots in the EThekwini Environmental Services Management Plan (EESMP) open space system



2.2 Carbon sampling

a Forest, woodland, and thicket

Carbon densities for eThekwini Municipality's forest and woodland types were estimated with data collected in $400m^2$ circular (11.3 m-radius) inventory plots. Plots positions were recorded using a GPS unit and geo-referenced to the EESMP GIS (*Figure 1*). 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 (to 30cm depth)

The carbon density of the live tree pool in each plot was calculated from **biomass density** (mass dry biomass per unit area) assuming 50% of vegetative biomass is carbon (MacDicken, 1997; IPCC, 1996). To quantify aboveground biomass, tree and liana diameters were recorded at 1.3 m from the ground (**diameter at breast height or dbh**) where dbh was 5cm or greater. Tree heights were estimated using a clinometer. The species of each measured tree was recorded and an **importance value** of each species observed in a cover 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 and liana was calculated based on diameter using a variety of generalized allometric equations appropriate for dry (MAP<1500mm) tropical regions, and where available, species specific equations (*Table 2*). **Allometric biomass equations** are derived from destructive sampling in which a variety of different sized trees are cut down and completely dried to find total biomass. Regression analyses of biomass and biometric measures reveal best fit relationships between measures of height, diameter, wood density, etc. Published mean values for species wood densities were used as available, and where not available, values were estimated from species of the same genus using wood hardness descriptions in qualitative species details given in *The Complete Guide to Trees of Natal, Zululand, and Transkei* (Pooley, 2003). Wood densities used are listed in *Appendix C*. A sensitivity analysis of the results using different allometric equations was used to assess the most appropriate and conservative equation.

Belowground tree biomass (BGB), or root biomass, 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):

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

Table 2 Generalized and species specific allometric equations used to estimate aboveground biomass. Equations have been modified from their published originals such that:

B = aboveground biomass (kg); D = dbh (cm); H = height (m); p = wood density (g/cm^3) ; A = basal area (cm^2); C = circumference (cm)

Allometry for:	**Equation formula**	**r^2**	**Sample size (n)**	**Dbh range (cm)**	**Location**	**Source**
			GENERALIZED			
Mixed species of tropical trees in dry conditions	$B = \exp[-1.996 + 2.32 \ln D]$	0.89	28	5-40	India	Brown 1997
Mixed species of tropical trees in dry conditions	$B = \exp[-2.187 + 0.916 \ln (pD^2H)]$	0.96	404	5-63	India, Australia, Mexico	Chave et al. 2005
Mixed species of tropical trees in dry conditions	$B = p * \exp[-0.667 + 1.784 \ln D + 0.207 (\ln D)^2 - 0.0281(\ln D)^3]$	0.96	404	5-63	India, Australia, Mexico	Chave et al. 2005
Prestoea montana (palm) - for all palms, Brown 1997	$B = 4.5 + 7.7 H$	0.96	25		Puerto Rico	Frangi & Lugo, 1985
Mixed liana species	$B = 10^{(0.12 + 0.91 \log A)}$	0.82	17	1-12	Venezuela	Putz 1983
			SPECIES SPECIFIC			
Eucalyptus grandis	$B = 2.3229 D^{0.2214}$	0.97	24	5-35	Australia	Birk & Turner 1992
Barringtonia racemosa	$B = p * (-0.03134 + 0.000446 D^2)$	0.98			Micronesia	Ewel et al. 2003
Dichrostachys cinerea (wood)	$B = 10^{(2.521 \log C - 2.460)}$	0.96	15	<100	South Africa	Shackleton 1997
Dichrostachys cinerea (leaves)	$B = 10^{(2.257 \log C - 3.043)}$	0.94	15	<100	South Africa	Shackleton 1997
Faurea saligna (wood)	$B = 10^{(2.606 \log C - 2.908)}$	0.96	15	<100	South Africa	Shackleton 1997
Faurea saligna (leaves)	$B = 10^{(1.855 \log C - 3.280)}$	0.89	15	<100	South Africa	Shackleton 1997
Combined savanna Euclea species (wood)	$B = 0.0001 * \exp[0.9107 \ln ((10D)^2 1000H) -3.6075]$	0.97	71	5-99	South Africa	Goodman 1990
Combined savanna Euclea species (leaves)	$B = 0.0001 * \exp[0.6357 \ln ((10D)^2 1000H) - 1.3575]$	0.82	71	5-99	South Africa	Goodman 1990
Combined savanna Acacia species (wood)	$B = 0.0001 * \exp[1.0432 \ln ((10D)^2 1000H) - 5.6181]$	0.97	210	5-98	South Africa	Goodman 1990
Combined savanna Acacia species (leaves)	$B = 0.0001 * \exp[0.8244 \ln ((10D)^2 * 1000H) - 4.8895]$	0.88	210	5-98	South Africa	Goodman 1990
Musa species (banana) - conservative estimate for *Strelizia nicoli*, banana family	$B = 0.0077159 D^2 + 0.049603 D - 0.10922$	0.96	22	1-23	Peru	Henman 2005
Sclerocarya birrea (wood)	$B = \exp[0.3086 \ln (100D^2) - 9.5446]$	0.98	30	4-33	South Africa	Scholes unpub
Sclerocarya birrea (leaves)	$B = 0.0074 D^2 + 0.0038$	0.79	33	5-50	South Africa	Scholes 1988

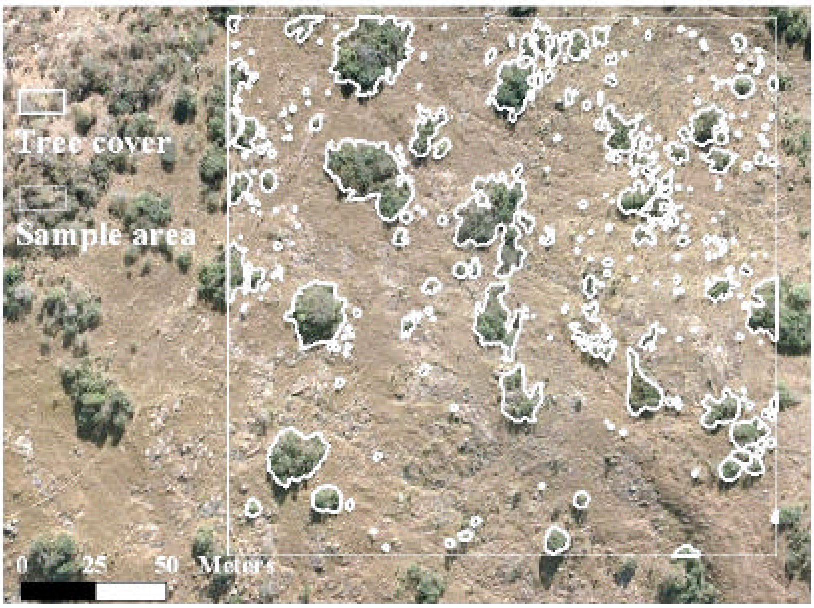
Coarse deadwood biomass was estimated in each plot using the transect method described by Harmon & Sexton, 1996. Diameters were recorded for all downed trees and branches with diameters=10 cm crossing two perpendicular transects (the north-south and east-west diameters of the inventory plot). Each piece 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 et al., 2003. **Standing dead trees** were measured with the live trees, but given decomposition rankings and structural rankings (stump, snag, large branches only, small branches only, only leaves missing) with which to scale down biomass.

Clip plots were used to measure **herbaceous vegetation** (and understory shrubs) 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 subplots was cut and weighed in field. The sample was well mixed and a 100-200g sub-sample taken to be oven dried to constant weight. 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.

Two **soil** samples were collected per plot from the bare ground revealed after clearing vegetation and litter from clip-plots. Soil cores were taken with a tube corer to a depth of 30 cm and separated into 15 cm intervals. Samples were air-dried, passed through a 2mm sieve, and subsequently weighed. Bulk density (grams soil/volume) was calculated based on soil texture and organic content as in Rawls 1983. Sample carbon concentrations were measured with a CN analyzer by the Soil Science Laboratory of the KZN Department of Agriculture and Environment (DAEA). The average carbon concentration at each depth was found and multiplied by bulk density to estimate **soil carbon density (tC/ ha)** to a 30cm depth.

One cover class, Coastal Bushclump Grassland Mosaic, consisted of two distinct cover types: open grassland and patches of trees and shrubs. This cover class was sampled with paired bushclump and grassland plots. Carbon densities were established separately for the two types and these were scaled by their mean percent cover before being summed to estimate carbon density per hectare of the 'mosaic.' Mean percent bushclump cover and grassland cover for Bushclump Grassland Mosaic throughout the EMA was estimated with aerial photographs. Using GIS, 40,000m^2 sample areas were drawn in randomly picked sites throughout the open space system and all bushclumps in the were manually traced (*Figure 2*). The same procedure was used to estimate tree cover in Wooded Grassland and Disturbed Woodland for comparison, although these were sampled as single coherent cover types.

Figure 2 Sample of woodland tree cover estimation from aerial photography using GIS



b Grasslands

Grassland carbon density was estimated for three carbon pools:

- Aboveground herbaceous biomass (living and dead)
- Belowground biomass
- Soil (to 30cm depth)

In each plot, aboveground herbaceous biomass was sampled in four 0.5 x 0.5 m clip-plots as described above for forest plots. Similarly a subsample was dried to ascertain wet:dry ratios for each plot and to calculate total biomass. Separating dead from live grass would have been inaccurate at best in dry conditions, thus no separation was made. Belowground biomass was estimated as a ratio of aboveground biomass using a ratio of 0.22 suggested by Fynn et al. 2005 from sampling South African grasslands in similar conditions: sandy soils and MAP 800-900mm. Unlike forest, grassland biomass was assumed to be 45% carbon (Brown, 1997). Soils were sampled using the same methods described above.

c Wetlands

Wetlands typically store large amounts of carbon in their soils with significant carbon stocks seen at greater soil depths than typically seen in dry ground ecosystems. This is because the relatively cooler and more anoxic conditions of water inundated soils slow the decomposition of organic material from litter and other inputs. For this study, wetlands were sampled in coordination with a research project by the Department of Geography & Environmental Science at the University of Kwa-Zulu Natal (UKZN) using different methodologies to those above (Hale, 2006).

At each wetland site, two transects were sampled. At the inland wetland sites, Alfred Park swamp forest and Roosfontein fresh water wetland, transects were roughly parallel to drainage lines with five to ten sampling points equally spaced along the lines between wetland boundaries. Wetland boundaries were delineated using visual soil analyses: 50 cm soil cores were taken at 10-15m intervals and assessed for evidence of seasonal or permanent water inundation such as mottles or gleying (Mitsch & Gosselink, 2000). Boundaries were surveyed and mapped using a dumpy level survey equipment and GPS. At the Umdloti estuary site, transects were arranged perpendicular to the shore line and were sampled until a water depth of 1m was reached or until the vegetation border yielded to open water. At this site the landward wetland boundary was delineated.

At each sampling point along the transect, soil cores were taken to 1-2 m depth depending on the water table and the depth to water or water height above ground. Soil cores were divided based on visual color/texture horizons. Each segment was dried and sampled for percent carbon using **loss on ignition (LOI)** in which samples were heated to 450°C for 8 hours and the mass lost was converted to carbon using the equation described in Craft et al 1991:

$$\text{Mass carbon} = 0.40\,(\text{Mass LOI}) + 0.0025\,(\text{Mass LOI})^2$$

Bulk density was calculated using dry weight (g) divided by core volume (cm^3). Vegetation and litter was sampled using 0.5m x 0.5m clip plots as described above.

Tree biomass in swamp forest was sampled as described for forest ecosystems at the Alfred Park swamp forest site. At the other two sites trees were measured similarly although in 5m radius plots at randomly picked sample points. Similar to the Bushclump Grassland Mosaic, the Umdloti site was a mosaic of reeds and patches of *Barringtonia racemosa* trees. For this reason carbon densities were averaged for reed plots and tree plots along the transect. Percent cover of each type was estimated from aerial photography as described for woodlands (section 2.2a, *Figure 2*). Carbon densities in the reed plots were used to estimate carbon for non-woody estuarine wetlands in the EMA.

2.3 Carbon density cofactors

Mean carbon densities were calculated for cover classes as defined by the EESMP, but these classes don't account for all the variation between carbon densities established for individual sample plots. While vegetative cover is to some degree determined by climate, soil, and terrain; however, even fairly specific, regional vegetation types such as Eastern Coastal Scarp Forest can occur on different soil types and survive a range of climate parameters (Eeley et al., 1999). Within a vegetation type, the density and size of the vegetation, and hence the carbon density, can vary significantly with biophysical and anthropogenic factors such as precipitation, slope, soil type and parent material, land use history and age, disturbances, and so on (Brown et al., 1995; Brown & Gaston; Chave et al., 2003). It is possible for this within-class variation to be equal or greater than between class variation and thus make the mean carbon densities of generally floristically or structurally different vegetation types statistically not differentiable. If statistically robust links can be made between these factors and carbon densities, carbon stocks can be more accurately estimated and mapped.

Spatially explicit data about some of these potential carbon cofactors was used to assess effects on carbon density variation within land cover classes using linear regression and comparisons of means. GIS layers of elevation, slope, and mean annual precipitation (MAP) were obtained from UKZN Geography Department and locations of rivers and underlying geology was obtained from eThekwini Municipality. It should be noted that these were meant to be exploratory rather than conclusive analyses because the sampling design of this study assumed no significant effect other than cover type, meaning that plots were randomly distributed within cover types without regard to capturing the variation of other cofactors. On a coarser scale, site specific carbon densities were compared within each sampled vegetation type to assess the cumulative impact of the different conditions at each site and give indication of the impact of site selection on the results.

2.4 Stock estimation and error analyses

The total carbon stock for eThekwini Municipality's open space system was calculated by multiplying the mean carbon density of each land cover type by its spatial extent. Standard errors were calculated for mean carbon densities and these were similarly scaled up to indicate the uncertainty in the final stock. In statistical comparisons of means an alpha of 0.05 was assumed unless otherwise indicated. Statistical tests were performed using JUMP 5.0.1 (SAS Institute Inc, 2003) software.

Aside from the uncertainty due to sampling error (sampling a limited number of plots across a heterogeneous landscape to represent the whole) as captured in standard error estimation, uncertainty was also introduced in the choice of allometric equations used to calculate biomass. Ideally local allometric equations should be made for the range of locally occurring species in local conditions, however, due to the time, resources, and amount of destructive sampling needed and with the existence of widely used generalized equations, this was deemed unnecessary. However, without destructive sampling, it is difficult to assess which of the published equations that fit eThekwini Municipality's climate, latitude, and or species are most accurate. For this reason a range of values from the different equations is presented.

2.5 *Modeling sequestration*

The Century Ecosystem Program (Parton et al., 1993) is a computerized ecosystem model that can be used to predict carbon dynamics in plant and soil pools over time under given climactic conditions. The model uses ecosystem starting biomass density, lignin content of plant material, soil texture and starting nutrient content, rainfall, temperature, and altitude to predict photosynthesis, vegetative and soil microbe respiration (hence litter decomposition), soil nutrient storage, and thus net biomass and carbon stocks. The model can also predict the amount of time an ecosystem would need to recover carbon stocks lost in disturbances and the accumulation rate over that period.

Mr. Tony Knowles of the University of Stellenbosch has calibrated the Century model (version 4.0 DOS) for various South African ecosystems, and used the data gathered in this study to calibrate the model for the wooded EMA ecosystems (Knowles, 2006). In addition to the inventory data collected as described above, ecosystem lignin content was estimated by analyzing lignin content in the species with the greatest importance value for the ecosystem. Leaf samples were taken from several trees of these species, oven dried, and ground to 2mm. Samples were tested for lignin content using the acid detergent lignin (ADL) method (Goering &Van Soest. 1970) by the Agricultural Research Council Laboratory Facility, Pretoria.

The model also required long term climate data (dating back several decades at least) to calibrate; therefore temperature and rainfall data were obtained for the Mt. Edgecome Station from Weather SA (http://www.saweather.co.za). While this station is located just north of the Durban City Center, it was the only station with enough uninterrupted, high quality data to calibrate the Century models. The data from this station did not differ notably from the sets of data available elsewhere in the EMA (Bluff, Botanic Gardens, Durban Airport, Pinetown, and Shongweni) (Knowles, 2006).

The Century model includes submodels for grassland, forest, or savanna systems. Wooded Grassland and Coastal Bushclump Mosaic were modeled as savanna type, while the more dense woodlands, Dry Valley Thicket and Alien Woodland were modeled as having forest-like dynamics. Input variables were used to calibrate the model's equations relating to ecosystem processes for each individual cover class. The calibrated model will then predict the currently observed mean carbon density over centuries if none of the input variables change.

After model calibration, several change scenarios were inputted in the model and biomass accumulation rates (hence carbon accumulation rates) were calculated for a 50 year interval after the change was introduced into each cover class:

- To estimate recovery rates of disturbed ecosystem, a disturbance removing all but 10% of the biomass was assumed. This could occur in overgrazing, over harvest, or fire. These data can help assess timelines of carbon storage in rehabilitation efforts. They also suggest potential sustainable resource harvesting rates to maintain carbon stocks on land while also supplying resources to dependent communities.

- To estimate the effects of climate change on biomass accumulation, various predicted changes in temperature, precipitation, and atmospheric CO_2 were input into the model for the years 2000-2050. Changes were introduced to both the stable and the disturbed states (described above) of the ecosystem types. Predicted parameter changes were obtained from the IPCC Data Distribution Centre (DCC, http://ipcc-ddc.cru.uea.ac.uk). The IPCC has devised several global development scenarios that assume different demographic, economic, and technological trajectories and calculated predicted future CO_2 emissions for each one

(Nakicenovic *et al.*, 2000). A high (A2) and a low (B1) emissions scenario were picked to assess the range of possible results.

- A2 assumes a continually growing global population in a heterogeneous world characterised by national self-reliance and regional orientated per capita economic growth. Forecasted emissions are 1862 GtC for 1990-2100 with a 3.4 ^{o}C (2.0-5.4^{o}C) increase temperature.
- B1 assumes that the global population peaks at mid-century and then slowly declines while global development is convergent, focusing on sustainability, equity, reducing material intensity, and the introduction of clean efficient technologies. Forecasted emissions are 983 GtC for 1990-2100 with a 1.8 ^{o}C (1.1-2.9^{o}C) increase temperature.

Global Climate Models (GCMs) have been developed to predict regional climate changes that will result from the CO_2 levels in the IPCC scenarios. The regional predicted climate data from two commonly used GCMs, from the Centre of Climate System Research (CCSR) in Tokyo and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, was used for each scenario. This data was localized by applying the predicted changes to the climate data from the Mt. Edgecome Station (*Appendix N*).

The scenario data was summarized by calculating five year biomass accumulation rates over the 50 year period because sequestration based offset projects are commonly monitored on a 5 years basis and have a lifespan of 20-50 years.

3 Results

3.1 *Forest & Feral Plantation*

a Biodiversity and structure

Forest characteristics, such as canopy height, size distribution, stem density, and species wood density, determine the biomass carbon density of a forest. Structural variables, species composition, and distribution (*Tables 3 &4, Figure 3, Appendix B*) of the forest types sampled were found to be similar to those documented for other forests with similar classifications in more regional studies (Eeley et al.,1999; CSIR, 2003; Lawes et al., 2004). As described in these studies, there was a species continuum between forest types with overlapping physical ranges and multiple species occurring commonly across types. The plots sampled in each class generally matched the altitude and rainfall distribution of the cover type throughout the EMA (*Table 4*). The dominant species listed in *Table 3* were consistent with common species lists for corresponding cover types in DWAF's indigenous forest classification (CSIR 2003); however, a few dominant species in EMA forests sampled, such as *Anastrabe integerrinea* in Scarp Forest, were not considered dominants in the DWAF report indicating a locally unique assemblage. Full species lists are given in *Appendix D.*

Coastal Scarp Forest in the EMA was typically found on sloped ground on Natal Group sandstone (67% of scarp forest area) and Natal Granites (19%) with an altitude range of 4-826 m. Sampled plots had canopies of 8-25 m, somewhat below the 15-25 m range described for this type (CSIR, 2003; Lawes et al., 2004). In a meta-study of scarp forest studies elsewhere in KZN, Lawes et al. (2004) reported basal areas of 35-57 m^2/ha and stem densities of 385-613 stems/ha. EThekwini Scarp Forest had a lower average basal area of 27.5 m^2/ha, but the mean stem density of 515 stems/ha was similar, indicating a smaller tree size and likely lower carbon densities than other studied scarp forests.

EMA **Coastal Lowland Forest** was found predominantly on Berea Formation sands (50%) and Natal Group Sandstone (30%) with a lower altitude range (1-300m) than Scarp. Canopy heights (9-23 m) were similar to Scarp Forest sampled and larger than Coastal/Dune Forests sampled elsewhere in KZN (8-10 m; Lawes et al, 2004), however Coastal Lowland Forest in the EMA had a mean basal area (29 m^2/ha) and stem density (482 stems/ha) to the range sampled in KZN (17.4-37.4 m^2/ha, 254-510 stems/ha; Lawes et al., 2004).

Dune Forest in EMA was also located on Berea Formation sands (58%) as well as Beach sands (29%) at low altitudes (0-102 m). Dune forests had higher stem densities (686 stems/ha) of shorter trees (5-16 m canopy) than the other coastal types with a resulting lower mean basal area (21.5 m^2/ha). However, Dune Forest plots had the greatest concentration of higher wood density species, with a mean tree wood density of 0.72 g/cm^3, while Transitional, Swamp, and Scarp had lower mean wood densities (0.51-0.57 g/cm^2).

Swamp Forest was a rare cover type in EESMP, covering 0.13% of its area, and was therefore less intensely sampled with only one sample site. This site had a relatively high stem density (590 stems/ha) of large trees (17-21 m canopy) resulting in a basal area of 33.6 m^2/ha greater than the other sampled types. Swamp Forest was seen on Natal Sandstone (42%), Harbor Bed sands (23%), and Dwyka tillite (19%) over a range of altitudes (0-525 m).

Transitional Forest was a very heterogeneous cover class in that it incorporated regenerating and/or continually disturbed forest of multiple types and land use histories, and as a result occurs over a wide range of altitudes and rainfall levels. The species composition contained common forest species with some early succession species such as *Trema orientalis* and *Albizia adianthifolia* dominating. Consistent with its definition as disturbed, it had lower densities (280 stems/ha) of smaller (5-16 m canopy), lower wood density trees (0.54 g/cm^3) with lower species richness (32 species in sample) compared to other types.

Feral plantations were dominated by tall *Eucalyptus grandis* trees and so had a higher average canopy (23 m) size than indigenous forest. However, average tree density (252 stems/ha), basal area (13.6 m^2/ha) and mean wood density (0.51 g/cm^3) were lower than indigenous forest types. These areas are no longer managed for timber production and number of forest and woodland tree species were also seen colonizing these areas.

Table 3 Species importance values (IV) for top ten species in sampled forest types

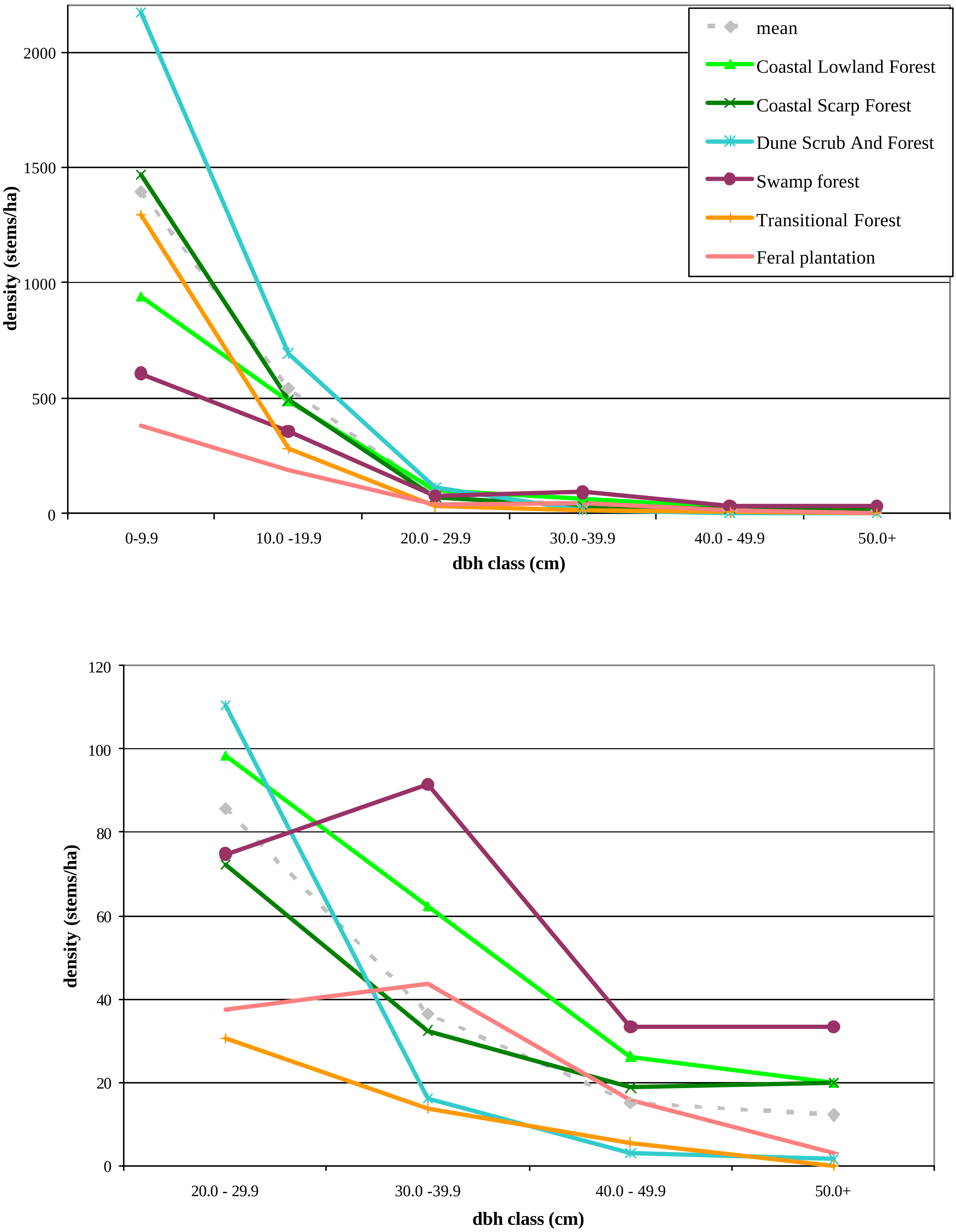
Coastal Scarp Forest		Coastal Lowland Forest		Dune Scrub and Forest	
Species	**IV**	**Species**	**IV**	**Species**	**IV**
Anastrabe integerrinea	10.2%	*Chaetacme aristata*	10.0%	*Mimusops caffra*	13.8%
Englerophytum natalense	9.1%	*Baphia racemosa*	5.4%	*Baphia racemosa*	10.5%
Protorhus longifolia	8.2%	*Albizia adianthifolia*	4.7%	*Euclea natalensis*	7.2%
Macaranga capensis	6.0%	*Cola natalensis*	4.2%	*Brachylaena discolor*	5.5%
Bridelia micrantha	4.0%	*Ficus natalensis*	3.9%	*Grewia occidentalis*	4.8%
Albizia adianthifolia	3.1%	*Croton sylvaticus*	3.6%	*Cola natalensis*	4.1%
Liana	2.9%	*Protorhus longifolia*	3.2%	*Dovyalis longispina*	3.4%
Tarenna pavettoides	2.5%	*Liana*	3.2%	*Chaetacme aristata*	3.2%
Rothmannia globosa	2.2%	*Strychnos usambarensis*	2.9%	*Celtis Africana*	3.2%
Tabernaemontana ventricosa	2.2%	*Rothmannia globosa*	2.4%	*liana*	3.1%

Swamp forest		Transitional Forest		Feral plantation	
Species	**IV**	**Species**	**IV**	**Species**	**IV**
Syzigium cordatum	23.2%	*Macaranga capensis*	11.6%	*Eucalyptus grandis*	48.8%
Voacanga thourarsii	11.7%	*Albizia adianthifolia*	10.0%	*Albizia adianthifolia*	11.0%
Tabernaemontana ventricosa	9.3%	*Trema orientalis*	8.3%	*Clerodendrum glabrum*	9.0%
Rothmannia globosa	6.8%	*Brachylaena discolor*	7.7%	*Antidesma venosum*	5.6%
Strelitzia nicoli	6.1%	*Strelitzia nicoli*	6.6%	*Apodytes dimidiata*	3.8%
Albizia adianthifolia	5.5%	*Bridelia micrantha*	5.3%	*Rhus pentheri*	3.4%
Macaranga capensis	5.1%	*Halleria lucida*	5.2%	*Strelitzia nicoli*	3.2%
Tabernaemontana ventricosa	4.0%	*Commiphora harveyi*	3.7%	*Dichrostachys cinerea*	2.7%
Phoenix reclinata	3.9%	*Sapium integerrimum*	3.7%	*Psydrax obovata*	2.0%
Tricalysia lanceolata	3.8%	*Baphia racemosa*	3.5%	*Ochna natalitia*	1.8%

Table 4 Structure and location characteristics of forest types sampled

Forest types	all EMA		Means & ranges for sampled plots							
	MAP (mm)	Altitude (m)	MAP (mm)	Altitude (m)	Slope (deg)	canopy height (m)	basal area (m^2/ha)	stem density dbh=10cm (stems/ha)	number species seen	wood density (g/cm3)
Coastal Scarp	766 (622-922)	324 (4-826)	799 (650-875)	380 (145-551)	14.5	17 (8-25)	25.7	515	92	0.57
Coastal Lowland	797 (788-805)	79 (1-300)	798 (775-825)	74 (24-120)	8.2	16 (9-23)	29.0	482	90	0.64
Dune	890 (798-911)	31 (0-102)	846 (825-875)	40 (1-100)	11.2	8 (5-16)	21.5	686	61	0.72
Swamp	800 (725-1000)	223 (0-525)	725	371	13.2	19 (17-21)	33.6	590	19	0.56
Transitional	744 (616-827)	247 (0-826)	769 (725-825)	339 (21-558)	8.8	8 (5-16)	9.5	280	32	0.54
Feral plantation	761 (604-817)	363 (6-744)	663 (625-675)	368 (309-438)	11.8	23 (19-27)	13.6	252	16	0.51

Figure 3 Stem size distributions (dbh = 5cm) for sampled forest types and feral plantation



b Carbon density

Estimated carbon densities for the municipality's forests (103 – 199 tC/ha) fit in the range of published estimates for other dry forests (MAP 0-1,500 mm) sampled around the world (*Table 6*). Scarp Forest (199±16 tC/ha) and Swamp Forest (197±33 tC/ha) had the greatest carbon densities of the forest types sampled, with the Scarp mean being significantly different from the other classes (*Table 5*). Swamp Forest was not sampled as intensely and thus had a greater standard error and less statistical significance in means comparisons. Coastal Lowland Forest had a significantly greater carbon density (166±10 tC/ha) than Transitional Forest and Feral Plantation, but wasn't statistically different to Dune Forest (133±8 tC/ha). The majority of the carbon stored was in tree biomass (19-63% of total) and soils (34-74%). Transitional Forest, which had the lowest carbon density (103±18 tC/ha), had lower tree biomass carbon stocks than other classes, but did not have significantly less soil carbon than other forest classes.

Tree aboveground biomass (AGB), one of the largest carbon pools, was estimated using the generalized equation from Chave et al. 2005 and species specific equations. This combination took the greatest number of variables into account: species, wood density, height, and diameter. The equation in Brown 1997 was solely based on dbh. However, the actual accuracy of these estimates over other equations cannot be tested without destructive sampling. Mean AGB carbon densities varied by 1-10 tC/ha with the choice of allometric equation; however, the differences were not statistically significant nor were they sizeable compared to the standard errors of the means (*Appendix F*).

Using Chave et al.'s 2005 equation generally resulted in lower carbon densities (3-20% lower) with greater relative standard error than when using Brown's 1997 equation (*Appendix F*). The effect of including height and wood density in Chave et al. was most evident in disturbed forest types: Transitional Forest, which had shorter and lower wood density trees than the other classes, had a mean AGB carbon density that was 17% lower using Chave et al. than Brown, while Feral Plantations, which had the tallest trees on average of any class, had a mean AGB carbon density that was 22% greater using Chave et al. The use of species specific equations generally increased carbon densities, but only made a notable difference for the Feral Plantation class: mean tree AGB carbon densities estimated with generalized equations for dry tropical conditions were 32.2-39.4 tC/ha, whereas means estimated using a species specific equation for *Eucalyptus grandis* trees were 52.8-52.9 tC/ha.

Diameter and height data for some sampled scarp and coastal forests elsewhere on the east coast was obtained from authors contributing to the DWAF forest classification report (CSIR 2003). Tree AGB carbon densities were calculated for these sites using Chave et al. to compare to EMA forest (*Appendix G*). The mean AGB carbon density (54±2 tC/ha) for all plots at these other coastal sites (Yengele, Dukuduku, Sodwana, Mapelane) was not significantly different from coastal and dune forest in the EMA. However, the scarp forests sampled elsewhere in KZN and the Eastern Cape had a mean AGB carbon density (173±13 tC/ha) significantly higher than for those in the EMA (66±9 tC/ha). While a few sites had AGB carbon densities in the range of those in the EMA (Nkandla: 86±11 tC/ha Hlati: 119±20 tC/ha), most were 100 tC/ha greater or more. It is possible the difference is linked to different rainfall, altitude, and geological conditions, but may also have to do with land use, disturbance, and management histories.

Table 5 Mean carbon densities by carbon pool for sampled forest types and feral plantation
*See *Appendix E* for p-values of pairwise comparisons.

Mean carbon density and standard error, s.e., (tC/ha)	**Coastal Scarp Forest (CSF)**	**Swamp Forest (SF)**	**Coastal Lowland Forest (CLF)**	**Dune Forest (DF)**	**Transitional Forest (TF)**	**Feral plantation (FP)**
plots (n)	20	3	20	17	9	8
Tree AGB	**66**	**99**	**75**	**40**	**15**	**45**
s.e.	*9*	*32*	*8*	*6*	*7*	*13*
% of total carbon	33%	50%	45%	30%	15%	37%
Tree BGB	**18**	**25**	**20**	**13**	**5**	**12**
s.e.	*2*	*7*	*2*	*1*	*2*	*3*
% of total carbon	9%	13%	12%	9%	5%	10%
greater than (p<0.05)*	DF, TF, FP	CSF, DF, TF, FP	DF, TF, FP	TF		TF
Herbaceous	**1.0**	**3.5**	**0.8**	**1.8**	**2.4**	**1.7**
s.e.	*0.4*	*0.0*	*0.3*	*0.5*	*0.7*	*0.3*
% of total carbon	1%	2%	1%	1%	2%	1%
greater than (p<0.05)*		CSF, CLF			CSF, CLF, DF, FP	
Standing dead trees	**2.6**	**1.0**	**1.3**	**1.1**	**0.7**	**0.8**
s.e.	*1.4*	*0.9*	*0.4*	*0.4*	*0.3*	*0.4*
% of total carbon	1%	0%	1%	1%	1%	1%
greater than (p<0.05)*	DF, TF					
CDW	**8.0**	**2.1**	**4.5**	**1.5**	**1.5**	**2.5**
s.e.	*3.3*	*0.9*	*1.8*	*0.5*	*1.4*	*0.7*
% of total carbon	4%	1%	3%	1%	1%	2%
greater than (p<0.05)*	DF, TF, FP					
Litter	**3.7**	**3.2**	**3.8**	**4.5**	**2.7**	**3.1**
s.e.	*0.3*	*0.0*	*0.3*	*0.5*	*0.6*	*0.8*
% of total carbon	2%	2%	2%	3%	3%	3%
greater than (p<0.05)*				TF		
Soil to 30cm	**100**	**68**	**61**	**72**	**76**	**56**
s.e.	*10*	*5*	*2*	*4*	*21*	*6*
% of total carbon	50%	34%	37%	54%	74%	46%
greater than (p<0.05)*	CLF, FP					
TOTAL	**199**	**197**	**166**	**133**	**103**	**121**
s.e.	*16*	*33*	*10*	*8*	*18*	*20*
greater than (p<0.05)*	CLF, DF, TF, FP	TF, FP	TF, FP			

Table 6 Comparison of carbon densities for eThekwini forest types with published estimates for other dry (MAP<1500 mm) tropical forests

Location	Cover type	MAP (mm)	Altitude (m)	**Mean carbon density** and standard error, s.e. (tC/ha)						source
				Tree AGB	s.e	**Soil**	s.e	**Total**	s.e	
eThekwini	*Transitional Forest*	*769*	*339*	*15*	*7*	*76*	*21*	*103*	*18*	
Africa general	Dry forest	<1000	-	28		-		-		IPCC 1996
Mexico	Dry forest	679	50-160	35	3	76	8	139		Jaramillo et al 2003
Mozambique	Dry forest	<1000	-	35		-		-		IPCC 1996
eThekwini	*Dune Forest*	*846*	*40*	*40*	*6*	*72*	*4*	*133*	*8*	
Africa general	Moist forest, long dry season	1000	-	45		-		-		IPCC 1996
eThekwini	*Feral plantation*	*663*	*368*	*45*	*13*	*56*	*6*	*121*	*20*	
Kenya	Dry coastal forest	900	100	50	6	23	4	94	8	Glenday 2005
Mozambique	Moist forest, long dry season	1000	-	65		-		-		IPCC 1996
eThekwini	*Coastal Scarp Forest*	*799*	*380*	*66*	*9*	*100*	*10*	*199*	*16*	
Venezuela	Dry forest	1500	130	70		110		221		Delaney et al 1997
eThekwini	*Coastal Lowland Forest*	*798*	*74*	*75*	*8*	*61*	*2*	*166*	*10*	
Senegal	Dry forest	843	-	88		41		-		Liua et al. 2004
Ethiopia	Dry forest	600	-	93	3	117		-		Michelsen et al. 2004
eThekwini	*Swamp Forest*	*725*	*371*	*99*	*32*	*68*	*5*	*197*	*33*	
Southern USA	Riparian wetland forest	1520	330	102	-	-	-	-	-	Giese et al. 2003
Kenya	Riparian forest	500	300	128	15	48	7	220	17	Glenday 2005

3.2 Woodland & thicket

a Biodiversity and structure

Woodland and thicket types sampled in the EMA had distinct structural characteristics and species assemblages from the sampled forests and, to some degree, from one another, although some tree species were common across types (*Table 8*). As expected, woodland and thicket types were found in areas with somewhat less rainfall and had shorter canopies with lower stem densities and basal areas than forests, but a species composition that had similar or greater mean wood densities (*Tables 4 & 9*). The indigenous cover types had characteristics similar to those described for KZN savannas by Low & Rebelo (1996).

Dry Valley Thicket/Broadleaf Woodland was primarily found on Natal Granites (48%) and Natal Sandstone (22%) at a range of altitudes and rainfall range slightly lower than the other woodlands. Sampled areas had loosely closed canopies 6-13 m tall with stem density (477 stems/ha) and basal area (17.2 m^2/ha) lower than those of intact forest but greater than Transitional Forest and other woodland. Dry Valley Thicket had greater stem densities of both small and large trees than other woodlands (*Figure 4*). This type was similar to Low & Rebelo's 'valley thicket' in its closed canopy and *Euphorbia spp*. dominants.

The more open indigenous cover types, **Coastal Bushclump Grassland Mosaic** and **Wooded Grassland,** had structures that corresponded well to Low & Rebelo's descriptions of 'coastal bushveld/grassland' and 'coastal-hinterland bushveld.' Bushclump Grassland in the EMA was found almost exclusively on Natal Sandstone (86%), while Wooded Grassland occurred on both Natal Sandstone (39%) and Granite (40%). Many tree species found dominating the bushclumps in the sample were similar to those found in indigenous forest, such as *Protorhus longifolia* and *Croton sylvaticus*, unlike Wooded Grassland which was dominated by *Acacia spp*. Bushclump grassland had trees in distinct clusters while Wooded Grassland had dispersed single trees, but the estimated tree canopy covers over sample areas of each type were not statistically different (18-20%, *Table 7*). Bushclump Grassland had slightly higher stem density (175 stems/ha) and basal area (4.8 m^2/ha) and taller trees (6-11m canopy) than Wooded Grassland (111 stems/ha, 3.0 m^2/ha, 3-7 m canopy), but Wooded Grassland species had higher mean wood density (0.66 g/cm^3 vs. 0.63 g/cm^3)

The more disturbed cover types were more cursorily sampled than intact indigenous types for reasons described above, however, samples taken generally reflected expected trends. **Disturbed** and **Alien Woodlands** and **Alien Thicket** all had significant area on Natal Sandstone (36%, 34%, 36% respectively), but Disturbed Woodland was also found on Natal Granite (29%) and Alien Woodland and Thicket on Dwyka tillite (36%, 28%). Both woodland types were dominated by alien syringa trees (*Melia azedarach*), but indigenous woodland species seen in other woodland types, such as *Acacia*, *Combretum*, and *Rhus* species, were common in Disturbed Woodland while Alien Woodland was almost completely composed of alien invasive species. While these species grew to be larger than those in other classes, with canopies 7-13 m and more large dbh trees than other classes (*Figure 4*), the mean wood density was low (0.54 g/cm^3). The Alien Thicket sample was perhaps less dominated by aliens than expected, however it had shorter (4-6m) trees and shrubs with higher mean wood densities than the two woodlands.

In accordance with its description 'disturbed,' Disturbed Woodland had relatively low stem density (139 stem/ha) and basal area (4.5 m^3/ha) compared to other types. It had significantly greater canopy cover (35%) than the naturally open woodland types, Bushclump and Wooded Grasslands. However, a visual survey of Dry Valley Thicket/Broadleaf Woodland and the Alien Woodland and Thicket classes with aerial photography showed these classes to have almost closed canopies that would have been difficult to map, unlike the more open Disturbed Woodland class.

Table 7 Tree canopy cover in sampled woodland types as assessed with aerial photography

Cover type	Sample area sites	Total area assessed (ha)	Mean canopy cover (%)	s.e.	greater than ($p<0.05$)
Wooded Grasslands	8	32	18%	3%	
Bushclump Grassland Mosaic	9	38	20%	5%	
Disturbed Woodlands	9	36	35%	5%	WG, BC

Table 8 Species importance values (IV) for top ten species in sampled woodland and thicket

*alien species

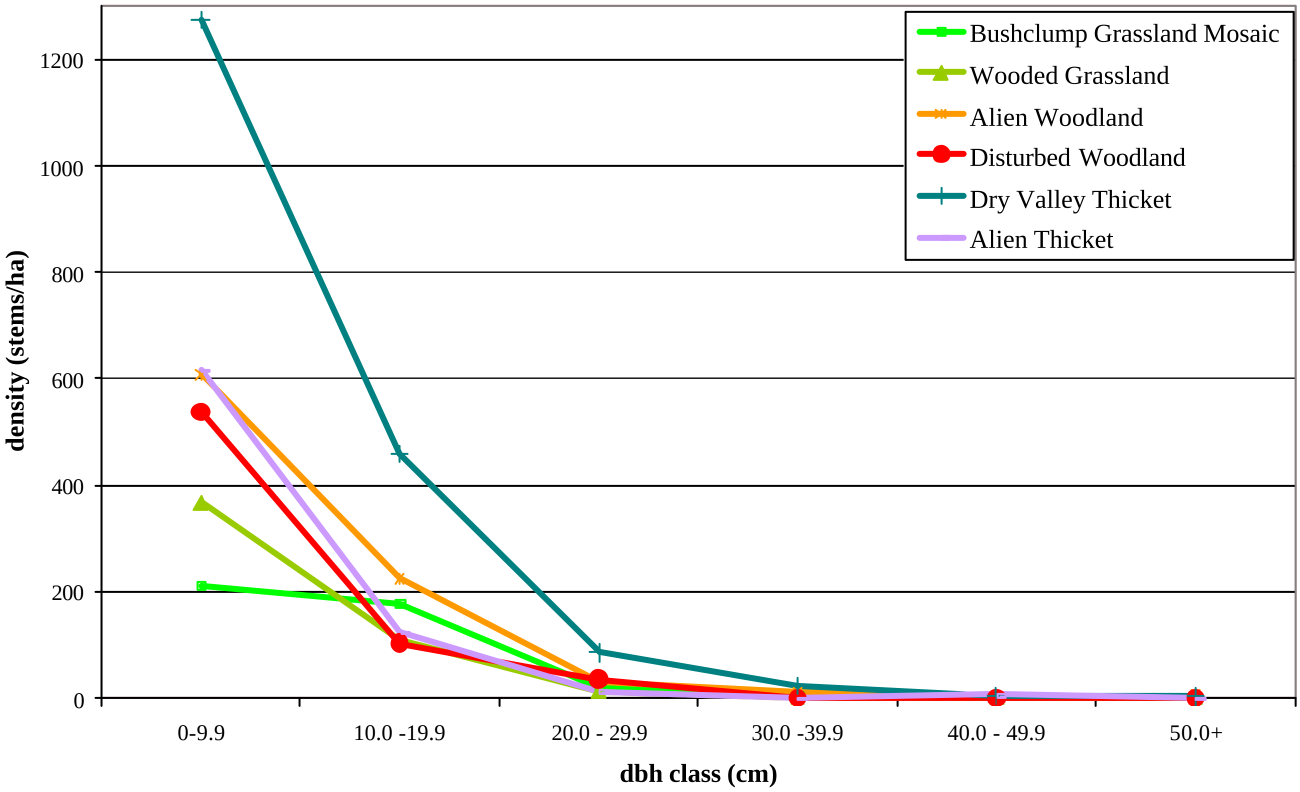
Dry Valley Thicket		Disturbed Woodland		Alien Woodland	
Species	**IV**	**Species**	**IV**	**Species**	**IV**
Spirostachys Africana	11.0%	*Melia azedarach**	15.2%	*Melia azedarach**	39.2%
Euphorbia tirucalli	9.8%	*Acacia sieberiana woodii*	12.6%	*Lantana camara**	10.3%
Combretum molle	7.0%	*Dichrostachys cinerea*	10.4%	*Rhus chirindensis*	8.4%
Acacia ataxicantha	4.4%	*Acacia nilotica*	8.0%	*Bridelia micrantha*	6.6%
Grewia occidentalis	4.1%	*Rhus chirindensis*	7.1%	*Morus alba**	6.5%
Euphorbia ingens	3.8%	*Acacia natalitia*	6.0%	*Solanum mauritianum**	5.4%
Cussonia spicata	2.7%	*Antidesma venosum*	4.0%	*Schinus terebinthifolius*	4.5%
Combretum kraussii	2.7%	*Albizia adianthifolia*	3.3%	*Cestrum laevigatum**	4.5%
Baphia racemosa	2.5%	*Combretum molle*	3.3%	*Psidium guajava**	2.8%
Wrightia natalensis	2.5%	*Bridelia micrantha*	3.2%	*Senna didymabotrya**	2.7%

Bushclump Grassland Mosaic		Wooded Grassland		Alien Thicket	
Species	**IV**	**Species**	**IV**	**Species**	**IV**
Croton sylvaticus	5.5%	*Acacia nilotica*	35.7%	*Rhus pentheri*	29.9%
Strelitzia nicoli	5.3%	*Acacia natalitia*	7.1%	*Acacia sieberiana woodii*	18.1%
Antidesma venosum	5.1%	*Albizia lebbeck*	6.3%	*Rhus nebulosa*	15.7%
Dalbergia obovata	5.0%	*Sapium integerrimum*	5.8%	*Schinus terebinthifolius*	11.4%
Liana	4.4%	*Acacia sieberiana woodii*	5.1%	*Melia azedarach**	4.6%
Ziziphus mucronata	4.2%	*Sclerocarya birrea*	4.7%	*Canthium inerme*	4.4%
Vepris undulate	4.1%	*Rhus pentheri*	4.4%	*Peddiea Africana*	4.0%
Protorhus longifolia	4.0%	*Heteropyxis natalensis*	3.2%	*Trichillia dregeana*	3.5%
Rapanea melanophloes	3.9%	*Ehretia rigida*	2.3%	*Dichrostachys cinerea*	3.0%
Dovyalis caffra	3.7%	*Gymnosporia buxifolia*	2.0%	*Ficus sur*	2.7%

Table 9 Structure and location characteristics of woodland and thicket types sampled

Forest types	All EMA		Means & ranges for sampled plots							
	MAP (mm)	Altitude (m)	MAP (mm)	Altitude (m)	Slope (deg)	canopy height (m)	basal area (m^2/ha)	Stem density dbh=10cm (stems/ha)	number species seen	wood density (g/cm3)
Dry Valley Thicket	685 (551-970)	388 (0-826)	707 (625-875)	416 (166-711)	15.5	8 (6-13)	17.2	477	77	0.62
Alien Woodland	766 (716-825)	117 (0-723)	785 (775-825)	101 (20-379)	2.7	13 (7-30)	8.5	244	11	0.54
Disturbed Woodland	725 (670-827)	280 (0-784)	761 (675-875)	225 (19-380)	4.2	7 (3-12)	4.5	139	24	0.65
Alien Thicket	757 (604-863)	199 (0-710)	825	99 (96-108)	3.2	5 (4-6)	5.2	143	14	0.67
Bushclump Grassland Mosaic	708 (645-755)	414 (35-763)	754 (725-775)	230 (142-377)	9.3	9 (6-11)	4.8	175	58	0.63
Wooded Grassland	710 (502-814)	430 (3-844)	681 (625-725)	348 (66-526)	7.6	4 (3-7)	3.0	111	28	0.66

Figure 4 Stem size distributions (dbh = 5cm) for sampled woodland and thicket areas



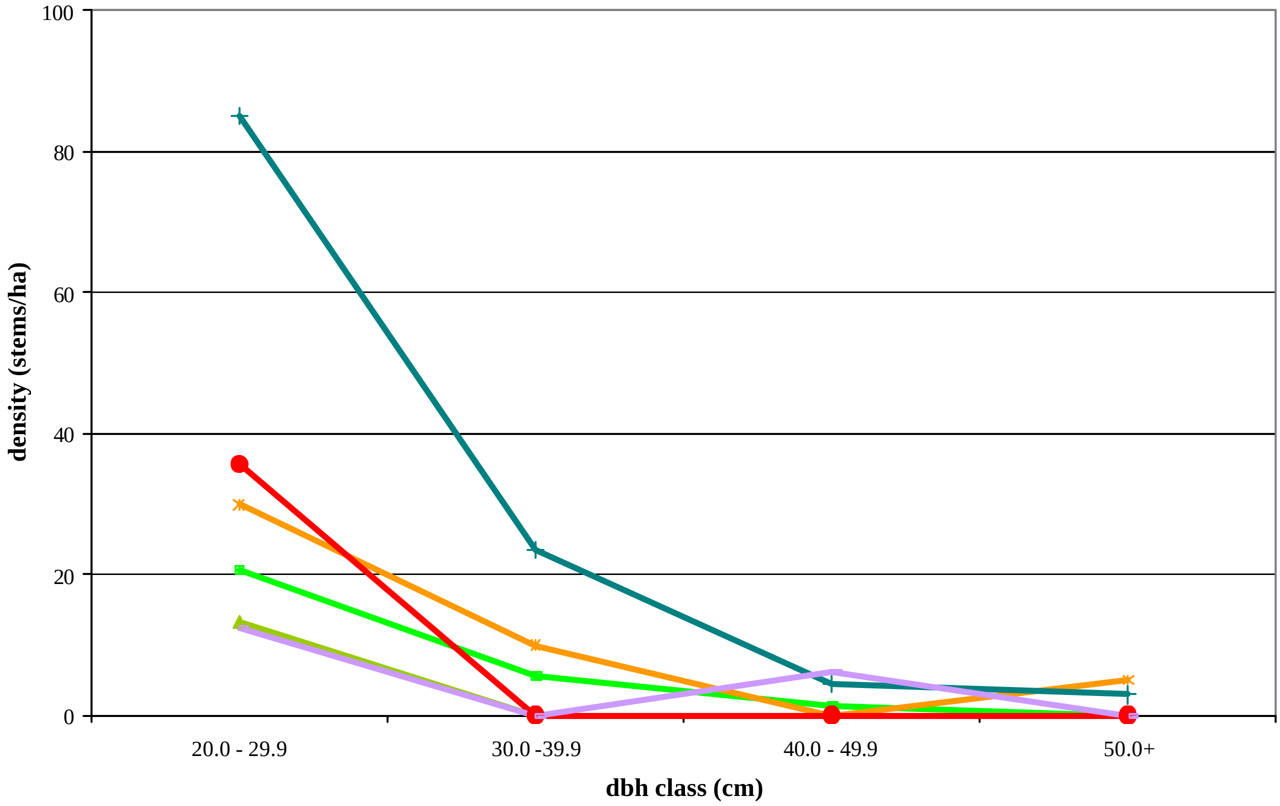


Table 10 Mean carbon densities by carbon pool for sampled woodland and thicket types

*See *Appendix E* for p-values of pairwise comparisons.

Mean carbon density and standard error, s.e., (tC/ha)	**Dry Valley Thicket/ Woodland (DV)**	**Alien Woodland (AW)**	**Bushclump Grassland Mosaic (BC)**	**Wooded Grassland (WG)**	**Disturbed Woodland (DW)**	**Alien Thicket (AT)**
plots (n)	17	5	7	17	7	4
Tree AGB	**29**	**14**	**7.9**	**4.7**	**9.1**	**8.8**
s.e.	*3*	*5*	*1.5*	*0.7*	*3.4*	*3.1*
% of total carbon	24%	15%	10%	7%	15%	17%
Tree BGB	**9.2**	**4.4**	**2.4**	**1.6**	**2.9**	**2.8**
s.e.	*0.9*	*1.6*	*0.4*	*0.3*	*0.9*	*0.9*
% of total carbon	8%	5%	3%	2%	5%	5%
greater than (p<0.05)*	BC, WG					
Herbaceous	**1.8**	**2.1**	**3.8**	**2.6**	**2.6**	**3.3**
s.e.	*0.4*	*0.5*	*0.4*	*0.5*	*0.5*	*0.6*
% of total carbon	1%	2%	5%	4%	4%	6%
greater than (p<0.05)*			DV			
Standing dead trees	**0.7**	**0.5**	**0.5**	**0.4**	**0.9**	**0.0**
s.e.	*0.2*	*0.3*	*0.1*	*0.2*	*0.9*	*0.0*
% of total carbon	1%	1%	1%	1%	2%	0%
greater than (p<0.05)*						
CDW	**0.8**	**0.8**	**0.3**	**0.0**	**0.1**	**0.0**
s.e.	*0.3*	*0.5*	*0.1*	*0.0*	*0.1*	*0.0*
% of total carbon	1%	1%	0%	0%	0%	0%
greater than (p<0.05)*						
Litter	**2.6**	**4.5**	**1.1**	**0.8**	**3.3**	**2.0**
s.e.	*0.3*	*0.8*	*0.2*	*0.6*	*1.2*	*0.6*
% of total carbon	2%	5%	1%	1%	6%	4%
greater than (p<0.05)*		DV, BC, WG, AT			BC, WG	
Soil to 30cm	**77**	**66**	**66**	**56**	**41**	**36**
s.e.	*8*	*1*	*9*	*5*	*11*	*2*
% of total carbon	63%	71%	81%	85%	68%	68%
greater than (p<0.05)*	WG, DW, AT					
TOTAL	**121**	**92**	**82**	**66**	**59**	**53**
s.e.	*9*	*6*	*11*	*5*	*14*	*5*
greater than (p<0.05)*	WG, DW, AT					

Table 11 Comparison of carbon densities for eThekwini woodland types with published estimates for other African woodlands

Location	Cover type	MAP (mm)	Altitude (m)	Mean carbon density and standard error, s.e. (tC/ha)						source
				Tree AGB	s.e	Soil	s.e	Total	s.e	
Nigeria	Open woodland	571	-	3		-		-		Mortimore et al 1999
Africa general	Thorn savanna	-	-	-		55		-		Scholes & Hall 1996
eThekwini	*Wooded Grassland*	*681*	*348*	*5*	*1*	*56*	*5*	*66*	*5.1*	
Senegal	Shrubland, isolated trees	340	-	7		25		32		Woomer et al 2004
eThekwini	*Bushclump Grassland*	*759*	*236*	*8*	*1*	*66*	*9*	*82*	*10.7*	
South Africa	Savanna	-	-	8		-		-		Rutherford 1979
eThekwini	*Alien Thicket*	*825*	*99*	*9*	*3*	*36*	*2*	*53*	*4.6*	
eThekwini	*Disturbed Woodland*	*761*	*225*	*9*	*3*	*41*	*11*	*59*	*14.4*	
Zimbabwe	Savanna	500	-	10		-		-		Kelly & Walker 1976
South Africa	Broadleaf savanna	-	-	13		72		94		Woomer 1993
eThekwini	*Alien Woodland*	*785*	*101*	*14*	*5*	*66*	*1*	*92*	*5.9*	
Zimbabwe	Broadleaf woodland	-	-	15		-		-		IPCC 1996
Ethiopia	Woodland	900	650	28	11	180		-		Michelson et al 2004
Nigeria	Open forest	571	-	29		-		-		Mortimore et al 1999
eThekwini	*Dry Valley Thicket/Woodland*	*707*	*416*	*29*	*3*	*77*	*8*	*121*	*8.5*	
Zambia	Broadleaf woodland	-	-	41		-		-		IPCC 1996

b Carbon density

Mean carbon densities for woodland types in the municipality (53-121 tC/ha) generally corresponded well with published tree and soil carbon values for savannas and woodlands elsewhere in the nation and in Africa (*Table 11*). Dry Valley Thicket/Broadleaf Woodland had the greatest carbon density (121±9 tC/ha) of all classes, statistically different from the others except Alien Woodland. This class had a greater carbon density than would have been predicted for South African Broadleaf Woodland (94 tC/ha) as estimated by Woomer 1994; while the soil carbon densities were similar (77 vs 72 tC/ha). EMA Dry Valley Thicket/Broadleaf Woodland had greater tree biomass (29 vs 13 tC/ha).

Much of the carbon stored in EMA woodlands was stored in soils (63-85% of the total) while tree biomass generally made up a smaller portion (10-37%). Dry Valley Thicket/Broadleaf Woodland had the highest soil and tree carbon density. Disturbed woodland and Alien Thicket had the lowest soil carbon densities (41-36 tC/ha), and so, although they had greater tree biomass than the Wooded Grasslands (9 tC/ha vs 5 tC/ha), their total carbon densities were lower, although not statistically significantly so.

The generalized tree biomass equations used in this study were created in dry tropical forests rather than woodlands, but several species specific equations were available for South African savanna species (*Table 2*). Equation choice effected carbon densities more for woodlands and thickets than for forests because woodlands generally had shorter trees and only Chave et al's equation included a height variable. Thus tree AGB carbon means were lower (by 15-44%) using Chave et al. versus Brown (*Appendix F*). Using species specific equations, where possible, did not notably change estimates compared to values calculated using only Brown's equation, however they increased values by 2 to 47% compared to means calculated with only Chave et al's equation. This may mean Brown's equation provided a closer match to the species specific equations, however Chave et al. was used in conjunction with the species specific equations for a conservative estimate.

3.3 Grassland

As expected, soil carbon made up most of the carbon stored in the grassland classes sampled in the municipality (94-99% of the total carbon density, *Table 12*). The Parkland sampled had significantly higher soil carbon density (101 tC/ha) than Primary Grassland (58±8 tC/ha), as topsoil and fertilizer additions had been made to the park, while the primary grasslands were managed as natural ecosystems with no exogenous additions. The Secondary Grassland sampled had higher soil carbon than in Primary, although the difference was not statistically significant. By nature of being secondary, Secondary Grasslands will have varying land cover histories and their soils may have been fertilized in the past, increasing soil carbon, but may also have been heavily used and tilled, decreasing soil carbon.

A range of biomass and soil carbon values were found in the published literature for grasslands growing in relatively dry tropical areas and the grasslands in the EMA were on the higher end of the range (*Table 13*). EThekwini municipality's Primary Grasslands (86%) were almost all found on Natal Group Sandstone (*Appendix B*), and sandy soils are typically less fertile, storing less organic matter, than other types (Fairbanks, 2000). The sampled Primary Grassland had the same soil carbon density (58 tC/ha) as that found in other South African grasslands growing on sandy soils (Mills et al., 2004).

Table 12 Mean carbon densities by carbon pool for sampled grasslands

*See *Appendix E* for p-values of pairwise comparisons.

Mean carbon density and standard error, s.e., (tC/ha)	**Parkland (PL)**	**Secondary Grassland (SG)**	**Primary Grassland (PG)**
plots (n)	3	4	11
Herbaceous & litter	**0.9**	**3.2**	**3.9**
s.e.	*0.2*	*0.4*	*0.5*
% of total carbon	1%	4%	6%
greater than (p<0.05)			PL
Soil to 30cm	**101**	**71**	**58**
s.e.	*0*	*17*	*8*
% of total carbon	99%	96%	94%
greater than (p<0.05)	PG		
TOTAL	**102**	**75**	**62**
s.e.	*0.2*	*17*	*7*
greater than (p<0.05)			

Table 13 Comparison of carbon densities for eThekwini grasslands types with published estimates for other tropical grasslands

Location	Cover type	MAP (mm)	Altitude (m)	Mean carbon density and standard error, s.e. (tC/ha)						source
				Biomass	s.e	Soil	s.e	Total	s.e	
Senegal	Grassland	-	-	0.9		12		13		Woomer et al 2004
South Africa	Grassland (on sand)	300-1000	-	1.5		-		-		O'Connor 1986
Senegal	Cropland	843	-	2.4		22		24		Liua et al 2004
China	Grassland	-	350	3.2		-		-		Su et al 2005
South Africa	Grassland	844	-	5.7		37		42		Fynn et al 2005
Australia	Grassland	-	-	-		50		-		Chan et al. 1988
South Africa	Grassland (on sand)	1050	1700			58				Mills et al 2004
eThekwini	*Primary Grassland*	*757*	*523*	3.9	0.5	58	8	62	7	
Africa general	Grassland/savanna	"dry"	-	-		-		66		Jobbagy & Jackson 2002
China	Tropical Grassland	"dry"	-	1.2		73		74		Ni 2005
eThekwini	*Secondary Grassland*	*725*	*402*	3.2	0.4	71	17	75	17	
Argentina	Grassland/savanna	"dry"	-	-		85		-		Abril et al 1999
eThekwini	*Parkland*	*825*	*0*	0.9	0.2	101		102	0	

3.4 Wetland

The three wetland sites sampled were used to generalize about several wetland types in the open space system. Roosfontein, the Freshwater Wetland site, was primarily composed of reeds (*Phragmites*) with sparse short trees and shrubs at the edges, and was used to estimate the carbon density for both Freshwater Wetland and Floodplain nonwoody wetland. The Umdloti Estuary site was characterized as *Barringtonia racemosa* Forest in the EESMP classification; however, the treed areas appeared as discrete patches and thus many plots only contained reeds. These were averaged to generalize about nonwoody Estuarine Wetland. The treed patches were a monoculture of roughly 5m tall *B.racemosa* trees. Canopy cover for the site was found to be 31%, so the mean carbon density for the area was calculated as 31% of the tree plot carbon and 69% of the reed plot carbon across the different pools. The Swamp Forest site, Alfred Park, was sampled like the other forests, but the soils were sampled like the other wetlands and the results are also included in this section.

The actual area of wetland was delineated based on soil coring around the periphery, rather than using the mapped area in the EESMP which wasn't based on soil sampling. Delineated wetland areas at all sites were found to be notably smaller than the area in the EESMP, with 15-75% of the mapped area being actual wetland (*Table 14*). This has implications for estimating the total open space carbon stock. Umdloti wasn't included in this analysis as only the landward edge of the wetland was delineated and was found to be similar to the EESMP line.

Table 14 Delineated wetland area compared to EESMP mapped area for sampled sites

Study Site	Wetland type	EESMP map wetland area (ha)	Delineated wetland area (ha)	% of EESMP area
Alfred Park	Swamp Forest	7.8	1.2	15%
Roosfontein	Freshwater Wetland	0.29	0.22	75%

Like grasslands, soils were the dominant carbon pool in wetlands. Sampling soil to 1m as opposed to 30cm made a notable impact on wetland carbon density estimates (*Table 15*). Swamp Forest and Estuarine Wetlands had similar topsoil carbon densities, but Estuarine Wetland had the highest soil carbon if sampled to 100cm. Thus, while Swamp Forest total carbon density (197±33 tC/ha) was significantly greater than the other wetland types to 30cm, if the soil pool down to 1m was included, the *B. racemosa* Forest had the greatest mean carbon density (301±33 tC/ha), although not statistically different from Swamp Forest (287±35 tC/ha) and non woody Estuarine Wetland (244±61 tC/ha). Freshwater Wetland had significantly lower total carbon density (149±23 tC/ha) than all the other classes, having lower soil and reed biomass carbon.

The ratio of topsoil (30cm depth) carbon to soil carbon to 1m depth was similar for Freshwater and Estuarine Wetlands (21-27%), indicating greater carbon storage below the topsoil. This ratio was notably higher for Swamp Forest (44%). In a meta-study of carbon distribution through the soil profile, Jobbagy & Jackson (2000) found that the ratio of carbon in the top 20cm of forest soils was 50% of that in the top 1m, on average across a range of forest types. It appears that Swamp Forest soils were behaving somewhere between what would be expected for a forest and a wetland.

Carbon densities for trees, reeds, and soils were similar to those found in wetlands of similar types elsewhere (Table 16). This suggests that, despite small sample sizes, it is likely the results were indicative of actual densities at least in order of magnitude. The Freshwater Wetland had reed biomass values similar but slightly higher than *Phragmites* and cattail wetlands in Europe. Such data on African non-woody wetlands was not readily available in the published literature. Wetland soils in the EMA had carbon densities in the range estimated for general wetland soils (210 tC/ha) in a global metastudy by Mitra et al. (2005). The *B. racemosa* wetland had similar tree and soil carbon densities to mangrove forests in China, South Africa, and Mozambique. The mangroves sampled by Steinke et al. (1995) were in the Umgeni estuary in the EMA, and have thus grown under similar conditions and serve as a good indicator of the accuracy of the results in this study.

The choice of allometric equation significantly influenced carbon densities in wooded wetland types. Swamp forests had larger trees on average than other forest classes (*Table 4, Figure 3*) and the inclusion of this variable in Chave et al.'s equation resulted in the mean AGB carbon density 11% greater than when using Brown's (*Appendix F*). In the case of the *B. racemosa* wetland, the inclusion of the species' low wood density in Chave et al.'s equation yielded a much lower AGB carbon density (53% lower) than using Brown's, and the resulting value was indistinguishable to that from the species specific equation from Ewel et al. 2003.

Table 15 Mean carbon densities by carbon pool for sampled wetlands

*See *Appendix E* for p-values of pairwise comparisons.

Mean carbon density and standard error, s.e., (tC/ha)	**Swamp Forest (SF)**	**Estuarine wetland (*B. racemosa*) (EW/B)**	**Estuarine wetland (reeds) (EW/R)**	**Freshwater wetland (FW)**
plots (n)	3	2	2	2
Tree AGB	**99**	**42**	**0**	**0.3**
s.e.	*32*	*4*	*0*	*0.2*
% of total carbon	50%	31%	0%	1%
Tree BGB	**25**	**12**	**0**	**0.1**
s.e.	*7*	*1*	*0*	*0.1*
% of total carbon	13%	9%	0%	0%
Greater than ($p<0.05$)*	EW, FW			
Herbaceous	**3.5**	**5.4**	**11.7**	**9.6**
s.e.	*0.0*	*0.9*	*0.3*	*1.5*
% of total carbon	2%	4%	14%	21%
Greater than ($p<0.05$)*		SF	SF	SF, EW/B
Standing dead trees	**1.0**	**0.0**	**0.0**	**0.0**
s.e.	*0.9*	*0.0*	*0.0*	*0.0*
% of total carbon	0%	0%	0%	0%
Greater than ($p<0.05$)*				
CDW	**2.1**	**0.0**	**0.0**	**0.0**
s.e.	*0.9*	*0.0*	*0.0*	*0.0*
% of total carbon	1%	0%	0%	0%
Greater than ($p<0.05$)*				
Litter	**3.2**	**8.5**	**9.8**	*n/a – combined with herb because difficult to separate accurately*
s.e.	*0.0*	*0.3*	*0.9*	
% of total carbon	2%	6%	12%	
Greater than ($p<0.05$)*		SF	SF	
Soil to 30cm	**68**	**66**	**64**	**35**
s.e.	*5*	*8*	*7*	*6*
% of total carbon	34%	49%	77%	78%
Greater than ($p<0.05$)*				
TOTAL to 30cm	**197**	**135**	**83**	**45**
s.e.	33	13	11	9
greater than ($p<0.05$)*	EW, FW	FW		
Soil to 100cm	**157**	**233**	**225**	**139**
s.e.	10	31	24	21
% of total carbon	55%	77%	92%	93%
greater than ($p<0.05$)*		SF, FW	SF, FW	
TOTAL to 100cm	**287**	**301**	**244**	**149**
s.e.	35	49	61	23
greater than ($p<0.05$)*	FW	FW	FW	

Table 16 Comparison of carbon densities for eThekwini wetland types with published estimates for other wooded and non-woody wetlands

Location	Cover type	MAP (mm)	Altitude (m)	Mean carbon density and standard error, s.e. (tC/ha) Tree AGB	s.e	Herb	s.e	Soil	s.e	source
Estonia	cattail wetland	-	-	-		7.2		-		Maddison et al. 2005
Europe	phragmites wetland	-	-	-		7.5		-		Brix et al 2001
global metastudy	salt marsh	-	-	-		-		117		Chmura et al. 2003
eThekwini	*Freshwater wetland (reeds)*	*775*	*114*	*0*	*0*	*9.6*	*1.5*	*139*	*25*	
eThekwini	*Freshwater wetland (trees&reeds)*	*775*	*114*	*0.8*	*0.2*	*9.6*	*1.5*	*139*	*25*	
global metastudy	wetland	-	-	-		-		210		Mitra et al, 2005
eThekwini	*Estuarine wetland (reeds)*	*825*	*8*	*0*	*0*	*11.7*	*0.3*	*225*	*217*	
eThekwini	*Estuarine wetland (wooded)*	*825*	*8*	*42*	*4*	*5.4*	*0.9*	*233*	*225*	
China	mangrove	-	-	44		-		165		Tam et al. 1995
South Africa	mangrove	-	-	47	4	-		-		Steinke et al. 1995
Mozambique	mangrove	-	-	54		1.1		320		de Boer 2000

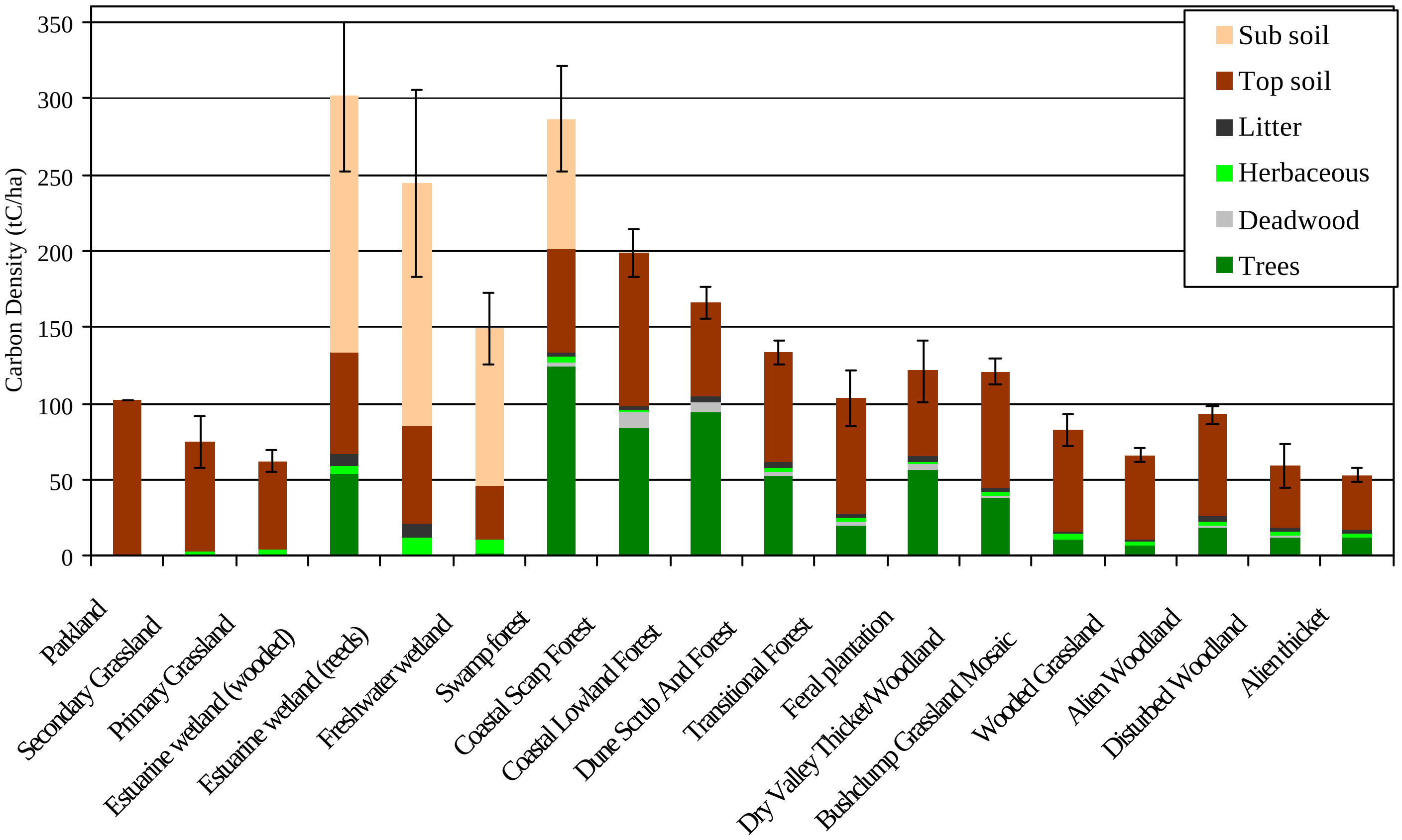
3.5 Cover type comparison

Land cover carbon density varies with a wide range of interacting factors. To use knowledge of relationships between carbon density and contributing factors to inform a carbon inventory of an area, these factors must be mappable. An obvious mappable factor is ecosystem type. It was expected that forests would store more carbon per hectare than woodlands and grasslands, and while this was generally so, using the finer classifications of forest and woodland in the EESMP it was found that this was not always the case (*Figure 5, Appendix E*). For example, Transitional Forest carbon density (103±18 tC/ha) wasn't statistically different from some woodland classes like Dry Valley Thicket (121±9 tC/ha) or Alien Woodland (92±6 tC/ha). Indigenous grassland mean carbon density (62±7 tC/ha) was slightly greater than, though not statistically different to, some disturbed wooded classes, like Alien Thicket (53±5 tC/ha), because the soil carbon in this class was statistically lower than in the grasslands by 22 tC/ha (*Appendix E*).

Except for the notably high topsoil (0-30 cm) carbon in Scarp Forest and Parkland and low soil carbon in Alien Thicket and Disturbed Woodland, all land cover classes had soil carbon densities between 55-75 tC/ha with few statistical differences although grasslands and wooded grassland were at the bottom of the range. If the subsoil is considered for wetlands, Estuarine Wetlands and Swamp Forests appear significantly more carbon rich than all other cover classes. Subsoil carbon storage was not sampled for other classes but is likely to be much less than in wetlands (Jobbagy & Jackson, 2000). Wetlands' deeper soil carbon stocks are due to their inundation slowing decomposition, a condition which can change with climactic change and hydrological alterations in watershed development. Thus this is a more vulnerable cover type carbon pool than subsoils of other cover types, which tend to be less carbon rich and more dependent on geology. In general the presence of forest and woodland primarily affect soil carbon storage in the top 30 cm (Brown 1997). For this reason carbon densities to 100 cm were used for wetlands in further calculations while 30 cm was used for other cover types.

Figure 5 Mean carbon density by cover type and carbon pool

Error bars represent standard error for mean total carbon density. Topsoil (0-30cm) was sampled in all classes, but subsoil (30-100cm depth) was only sampled in wetlands.



3.6 Carbon cofactors

Soils were a major carbon pool in all sampled ecosystems. **Geology**, a factor already mapped for the EMA, interacts with climatic and biotic factors to influence soil type and fertility. Generally speaking sandstones, granites, gneisses, and sand deposits produce soils that are less fertile (likely to store less carbon) than alluvium (flood deposited sediment) or finer sedimentary rocks like shale and tillite. Cover types mapped in the EESMP were typically associated with one or two geologies, but some cover types occurred on several fairly different bedrock types (*Appendix B*). While sampling was guided by cover type not geology, it was possible in some cases to make significant comparisons of mean plot soil and total carbon densities on different bedrock types within cover classes (*Appendix H*), the results of which are summarized as follows:

- In Coastal Lowland Forest and Transitional Forest, plots on **Natal Group sandstone** had greater *soil* carbon densities than those on Berea Formation sands (by 17 and 101 tC/ha $p<0.05$). Mean *total* carbon densities were also greater (by 36 and 67 tC/ha), although not statistically significant.

- In Disturbed Woodland and Wooded Grassland, **Dwyka tillite** plots had greater *soil and total* carbon densities than those on Natal sandstone (by 50 and 35 tC/ha for soil and 67 and 32 tC/ha for total, $p<0.05$).

- In Feral Plantation and Secondary Grassland, **Megacrystic biotite gneiss** plots had greater *soil* carbon densities than those on Natal Group sandstone (by 28 and 59 tC/ha, $p<0.05$). Mean *total* carbon densities were also greater (by 31 and 58 tC/ha), although not statistically significant for Feral Plantation. In Dry Valley Thicket/Broadleaf Woodland, Megacrystic biotite granite plots had a higher *soil and total* carbon than Natal Group sandstone, Natal Granite, and Biotite gneiss (by as much as 70 tC/ha).

In addition the effect of cover type on soil carbon density within a geology type was tested (*Appendix H*):

- Where **forests** occurred on a bedrock type, mean soil carbon was greater than for woodlands and grasslands with the same geology (by <20 tC/ha). Due to sample sizes, this result was only statistically robust for Natal Group sandstone, but the trend was repeated on Biotite gneiss and Natal granite.

- On Megacrystic biotite granite and Natal Sandstone, **Dry Valley Thicket** plots had significantly higher soil carbon density than other woodlands.

- **Alien infested vegetation** tended to have significantly lower soil carbon than other cover types, a trend seen on several bedrock types: Dwyka tillite, Megacrystic biotite granite, Natal Group Sandstone.

Other mappable abiotic factors, such as mean annual rainfall (MAP), altitude, and distance from river, were spatially continuous variables and thus tested for affect on plot carbon density within vegetation classes using simple regression (*Appendix I*).These factors and others interact to determine carbon storage. Individual factor effects may not be evident without controlling for the others, but there weren't enough plots over the full range of cover type and geology type combinations and abiotic gradient in the EMA to reliably test a multi-factorial carbon model.

The detectable effects of these variables on carbon were generally weak (*Appendix I*), in that the variable did not explain much of the variation in plot carbon densities within the ranges seen in each cover type, however a few trends emerged:

- Increased **altitude** had a positive correlation with total carbon in all forest types, but the maximum r^2 for all classes was 0.55 in Coastal Lowland Forest. The relationship was also weakly positive for dense woodland types, Dry Valley Thicket (r^2=0.54) and Alien Woodland (r^2=0.88), but negative for Wooded Grassland (r^2=0.24) and Disturbed Woodland (r^2=0.88). There was no clear relationship in grasslands.

- Increased annual **rainfall** within sampled ranges did not show an obvious relationship with carbon in forests or grasslands, but had a significant correlation with increased carbon densities in Disturbed Woodland (r^2=0.88) and Alien Woodland (r^2=0.89).

- Increased **distance from rivers** (or drainage lines) was weakly correlated with decreased carbon densities in forest types. The strongest relationship was seen in the Transitional Forest sample (r^2=0.72), mostly due to a correlation with decreased soil carbon (r^2=0.78). No obvious relationships were seen for woodlands or grasslands.

3.7 Site carbon density comparisons

The EMA's open space resource is very fragmented and thus cover types are found in patches distributed across a variety of conditions the ecosystem is compatible with. Comparing mean carbon densities between different sampled sites for a given cover type shows the combined affect of abiotic, biotic, and historical factors that may differ between sites. Disturbance patterns, historical use, and management are factors that have not been mapped thoroughly in the EESMP, but may have the dominant effect on carbon density variation within ecosystems.

A range of plot carbon densities was seen at each sample site (*Figure 6, Appendix J*) and thus, while mean carbon densities for different sites could be notably different, site mean variation within a cover class were generally not statistically significant at this level of sampling. A few sites did have discernibly different carbon densities from others of the same cover type:

- In **Coastal Lowland Forest**, Wentworth Forest had a lower mean carbon density (103±13 tC/ha) than Pigeon Valley, Hawaan Forest, and Stainbank Reserve (184-195 tC/ha). Wentworth also had the lowest altitude, was furthest from a river, had the shortest canopy, and had the lowest mean tree wood density.

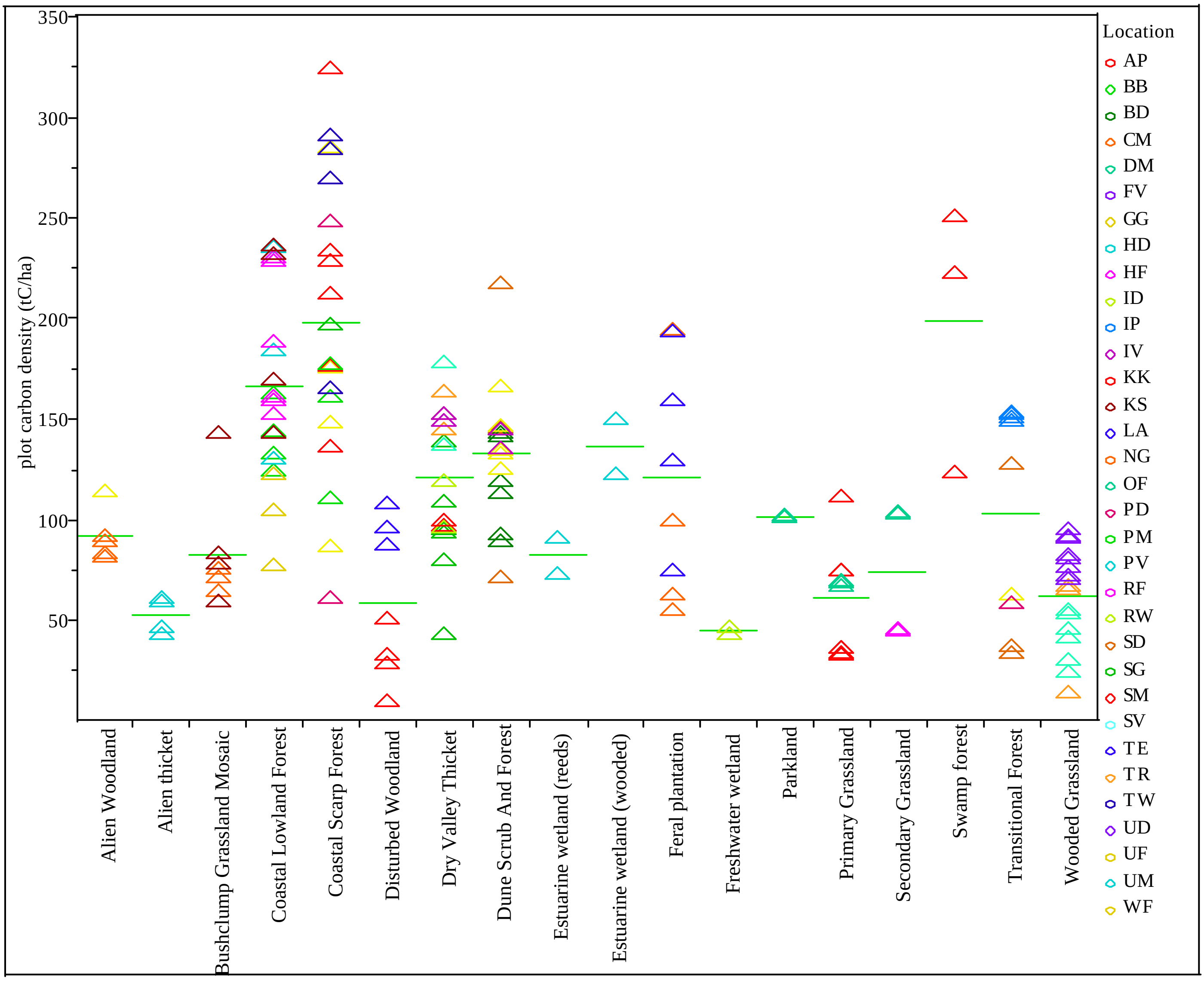
- In **Transitional Forest** Ipithi Reserve had a much higher mean carbon density (152±1 tC/ha) than the other sites (59-67 tC/ha) because of its high soil carbon. This site is a young (<10 yrs) managed regenerating forest on what was once a eucalyptus plantation on a river. Soils may have accumulated carbon due to former or current management, organic matter from the cleared plantation, and possibly alluvial sediment from the river. Plots at this site had the highest altitude and the least distance from a river. Interestingly, Ipithi had a greater mean carbon density than the feral eucalyptus plantation sites.

- In **Dry Valley Thicket/Broadleaf Woodland**, Shongweni Reserve had a lower mean carbon density (94±13 tC/ha) than Inanda Valley/Crestholme, Thornridge, and the Shongweni Valley sites (151-158 tC/ha), although was not out of the range of Krantzkloof, Summerveld, and Inanda Dam border (97-108 tC/ha)

- In **Disturbed Woodland** the Little Amanzimtoti site had significantly higher carbon density (98±6 tC/ha) than the Summerveld site (31±9 tC/ha). The former site, dominated by fairly large alien *M. azedarach* trees, had higher tree biomass carbon than the short *Acacia* dominated Summerveld. It also had higher soil carbon, perhaps due to Dwyka tillite bedrock likely producing more fertile soil than Natal Sandstone and/or the plots' close proximity to the river.

- In **Secondary Grassland**, the Drummond site had a much greater carbon density (104±1 tC/ha) than Roosfontein (45 tC/ha), because of its higher soil carbon storage which may be linked to its bedrock geology (Megacrystic Biotite Gneiss)

Figure 6 Plot total carbon density distribution by cover class and site



3.8 Total open space carbon stock & reliability

Using the carbon densities found in the fieldwork and literature as needed, the total carbon stock for the EMA's open space system, as mapped in 2005-2006 financial year, was 6.6±0.2 million tons of carbon (*Table 17*). This means that the ecosystems in the EESMP had collectively sequestered a net of 24.7± 0.6 million tons of carbon dioxide from the atmosphere. The majority of this stock was found in Dry Valley Thicket/Broadleaf Woodland (34%) and Forests (26%), the majority of which were Scarp Forest (*Table 17, Figure 7*).

Table 17 Carbon densities and carbon stock calculation for the EESMP (2005-2006)

Cover type	Area (ha)	Plots (n) / source	Carbon density (tC/ha)	std error	Carbon stock (tC)	std error	% of stock
Dry Valley Thicket/ Broadleaf Woodland	18,610	17	121	9	2,247,310	159,077	34%
Wooded Grasslands	11,393	30			815,078		12%
Unspecified	*7,226*	*9*	66	5	477,691	37,035	7%
Bushclump Mosaic	*3,785*	*13*	82	11	312,131	40,480	5%
Acacia Savanna	*362*	*8*	66	5	23,949	1,857	0%
Protea Woodland	*12*	*Wooded Grassland*	66	5	807	63	0%
Faurea Woodland	*8*	*Wooded Grassland*	66	5	499	39	0%
Forest	10,646	66			1,698,091		26%
Coastal Scarp Forest	*4,683*	*20*	199	16	931,226	75,321	14%
Transitional Forest	*3,072*	*9*	103	18	317,384	54,597	5%
Coastal Lowland Forest	*989*	*20*	166	10	164,439	10,388	2%
Dune Scrub and Forest	*925*	*17*	133	8	123,483	7,324	2%
Riverine Forest	*833*	*Forest mean*	165	8	137,830	6,362	2%
Unspecified	*143*	*Forest mean*	165	8	23,730	1,095	0%
Wetland (non woody)	5,706	13			858,767		13%
Floodplains	*4,988*	*Freshwater wetland*	149	23	742,708	116,010	11%
Freshwater Wetland	*621*	*6*	149	23	92,527	14,453	1%
Estuarine Wetland	*96*	*7*	244	61	23,532	5,894	0%
Alien Vegetation	3,787	17			291,214		4%
Alien Thicket	*1,964*	*4*	53	5	103,923	9,070	2%
Alien Woodland	*1,169*	*5*	92	6	108,082	6,861	2%
Feral Plantation	*653*	*8*	121	20	79,209	13,094	1%
Grassland	2,855	15			200,533		3%
Secondary Grassland	*1,889*	*4*	75	17	140,829	31,775	2%
Primary Grassland	*920*	*11*	62	7	56,779	6,732	1%
Not Applicable	*46*	*Grassland mean*	64	5	2,925	212	0%
Disturbed Woodlands	2,833	7	59	14	168,337	40,858	3%
Recreational *(parks)*	1,710	3	102		173,933	0	3%
Wetland Forest	208	5			65,507		1%
Swamp Forest	*85*	*3*	287	35	24,218	2,966	0.4%
Mangrove Forest	*56*	*Umgeni (Steinke et al 1995)*	375	18	21,115	1,036	0.3%
Not Applicable	*43*	*Estuarine wooded*	301	49	12,953	2,100	0.2%
Barringtonia racemosa	*24*	*2*	301	49	7,097	1,151	0.1%
Hibiscus tiliaceus	*0.4*	*Estuarine wooded*	301	49	123	20	0.0%
Settlements	903				47,747		1%
Rural Settlements	*803*	*Disturbed woodland*	59	14	47,747	11,589	1%
Field Crops	741				42,888		1%
Fallow Crop Lands	*409*	*secondary grass*	75	17	30,454	6,871	0.5%
Commercial Market Gardening	*199*	*fertilized, tilled fields on sandy soil (IPCC 1996)*	37		7,461	0	0.1%
Large Scale Commercial	*133*		37		4,973	0	0.1%
Tree Crops	14				1,422		0.0%
Plantations	*10*	*Glenday 2006, IPCC 1996*	85	21	835	206	0.01%
Fruit Trees	*4*		150	30	587	117	0.01%
Utility	289				8,949		0.1%
Cemetery	*84*	*Parkland*	102		8,523	0	0.1%
Grassed Road Verge	*5*	*Secondary Grassland on sand (Roosfontein)*	46		242	0	0.0%
Grassed Reservoir	*4*		46		184	0	0.0%
TOTAL (Mt C)					**6.6**	**0.2**	
TOTAL (Mt CO2)					**24.3**	**0.9**	

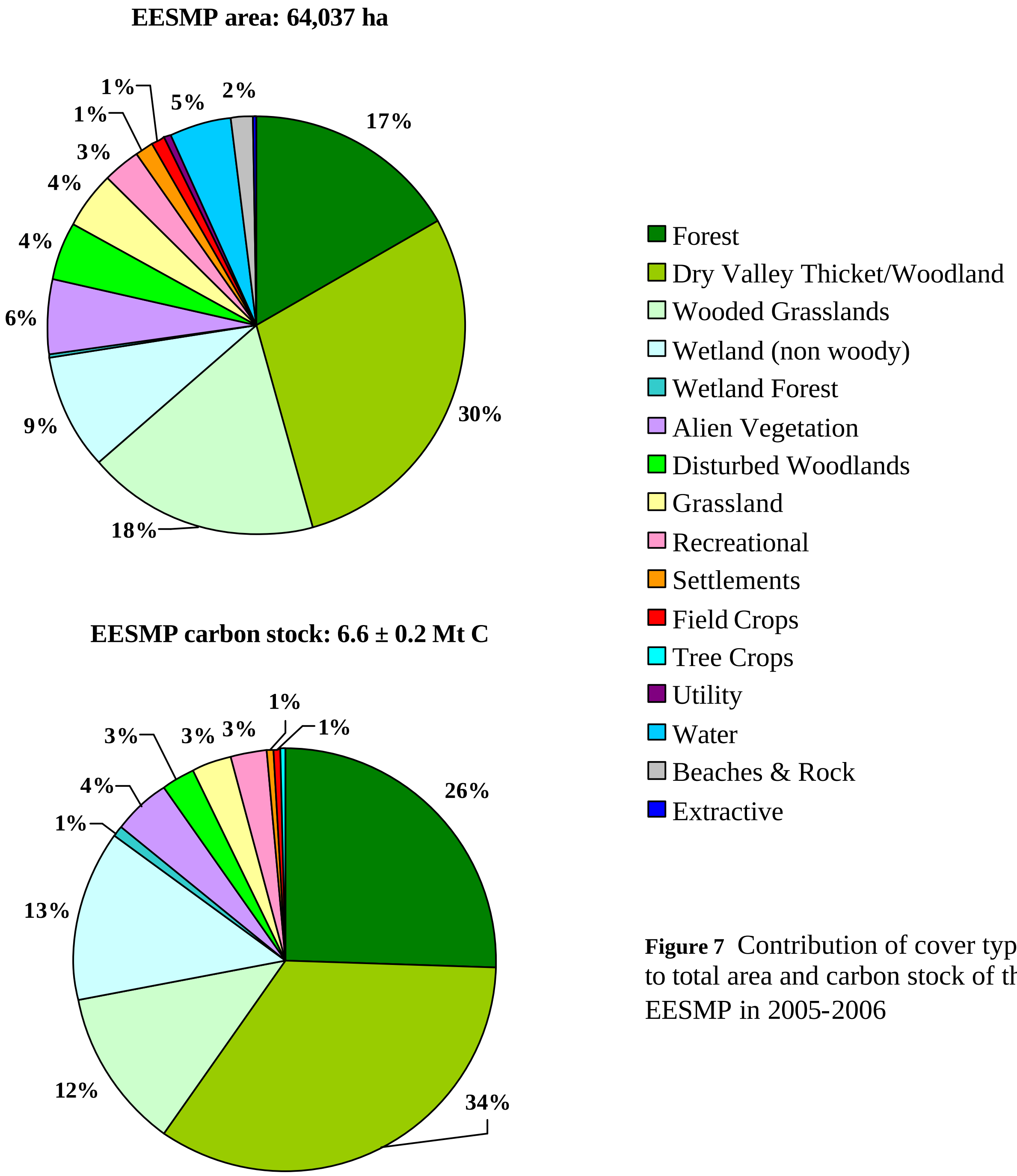


Figure 7 Contribution of cover types to total area and carbon stock of the EESMP in 2005-2006

Because of their relatively high carbon densities, Forest and Wetlands stored a greater proportion of the total carbon stock than their proportional area in the open space system, while the lower carbon densities in Wooded Grassland, Disturbed Woodland, and Alien Vegetation meant that they made up a lower percentage of the total stock than their spatial coverage (*Figure 7*).

This stock estimate relies on several assumptions regarding sampling and reliability of the plots sampled to represent the range of carbon densities in the EMA. However, the figure can be considered a realistic and relatively conservative for a number of reasons:

- The **choice of tree AGB allometric equation** generally did not produce large disparities in carbon density estimates compared to uncertainty from within class heterogeneity (standard error) but differences are magnified when scaling up to total stock. However, the chosen equation (Chave et al., 2005) was based on a large sample size, included several tree variables, and generally produced lower carbon densities, and so was assumed to produce conservative carbon estimates for comparing structurally diverse vegetation types.

- A lower **standard error** indicates more confidence can be placed in the estimated mean as being representative of the actual mean for the areas sampled. Standard errors were reasonably low, under 10% of the estimated mean, for the significant carbon storing classes: intact indigenous forest and Dry Valley Thicket. Classes with high standard errors (20-24%) were less significant in the total area and/or carbon stock; Disturbed Woodland, Secondary Grassland, and Freshwater Wetland.

- Most plots were located on the dominant **geological types** for their cover type (*Appendices B & H*). Where it appeared that geology might have influenced carbon in a cover type, the sample was generally skewed toward lower carbon density geologies (*Appendix H*).
    - This was not true in two cases: Wooded Grassland (too many Dwyka tilite plots) and Secondary Grassland (too many Megacrystic Biotite granite plots). Geology may have not been the only factor contributing to soil differences. A simple sensitivity analysis was used to check the effect on stock of adjusting mean carbon densities of these classes by their geological distribution (*Appendix K*). This decreased the stock estimate 0.2 Mt C, a change in the range of the standard error of the original figure.

- The range of **altitudes and rainfalls** sampled within each cover class was roughly representative of the mean if not the full range of conditions found in the EMA *(Tables 4 & 9*). Thus, while these factors may affect carbon densities within cover classes, it will be assumed that the sample used was representative in this regard. In addition, these factors generally did not have strong effects within the ranges sampled compared to the combined effect other uncontrolled variables.

- It appeared that the **choice of sample sites** should not have notably skewed mean carbon densities. For most sites, variation in plot carbon densities wasn't significantly different to that of the other sites in the cover type (*Figure 6*). Sites that were different from others in their cover class could not be clearly differentiated by mapped characteristics, with the exception of the differing geology of the secondary grassland sites (*Appendix J*). At this level of sampling, these sites cannot be reasonably excluded as outliers as they may represent the real variation in the cover type in the EMA.

- Mean carbon densities found in this study did not notably deviate from results for similar ecosystems in peer-reviewed **published literature**, even for the cover classes that were less well sampled. One deviation of note was found: EMA Scarp Forest had lower tree carbon than other samples in the east coast region. EMA Scarp may have naturally lower carbon densities due to lower rainfall, altitude, or coastal proximity, but may also influenced by fragmentation (small forest patches have more edges which tend to have lower biomass), disturbance or management history.

- The accuracy of **wetland mapping** could influence total carbon stock estimates. At the sites sampled, it was found the EESMP mapping of the wetland over-estimated actual wetland area (*Table 14*). If the differences in area seen at these sites was typical of all freshwater non-woody wetlands and swamp forest mapped in the open space system, the total carbon stock estimate may be lowered by 0.13 Mt C (*Appendix K*) still in the range of the original estimate. However, the trends from two sites may not be representative of wetland mapping throughout the EESMP.

3.9 *Vulnerability of open space carbon stock*

Not all of the EESMP is protected or zoned as open space. Large portions of the system are privately owned or zoned for development. Of this area, indigenous forest and wetlands are protected from development to a certain extent under the National Forest Act, National Water Act, and National Environmental Management Act (NEMA) Environmental Impact Assessment (EIA) regulations. Areas that are over-steep or within the hundred-year floodline are also considered undevelopable. The remaining open space that was considered vulnerable to development comprised 41,192 ha, 64% of the EESMP area, and stored an estimated 3.8 ± 0.2 Mt C, 58% of the total carbon stock, based on the same carbon densities used in the total carbon stock calculation (*Table 18*). Dry Valley Thicket/Broadleaf Woodland was the most vulnerable cover class in terms of carbon stock and the most vulnerable ecosystems in terms of potential percent area loss were Dry Valley Thicket, Wooded Grassland, and Grassland.

Figure 8 Carbon stock on developable and undevelopable areas of the open space system by cover class

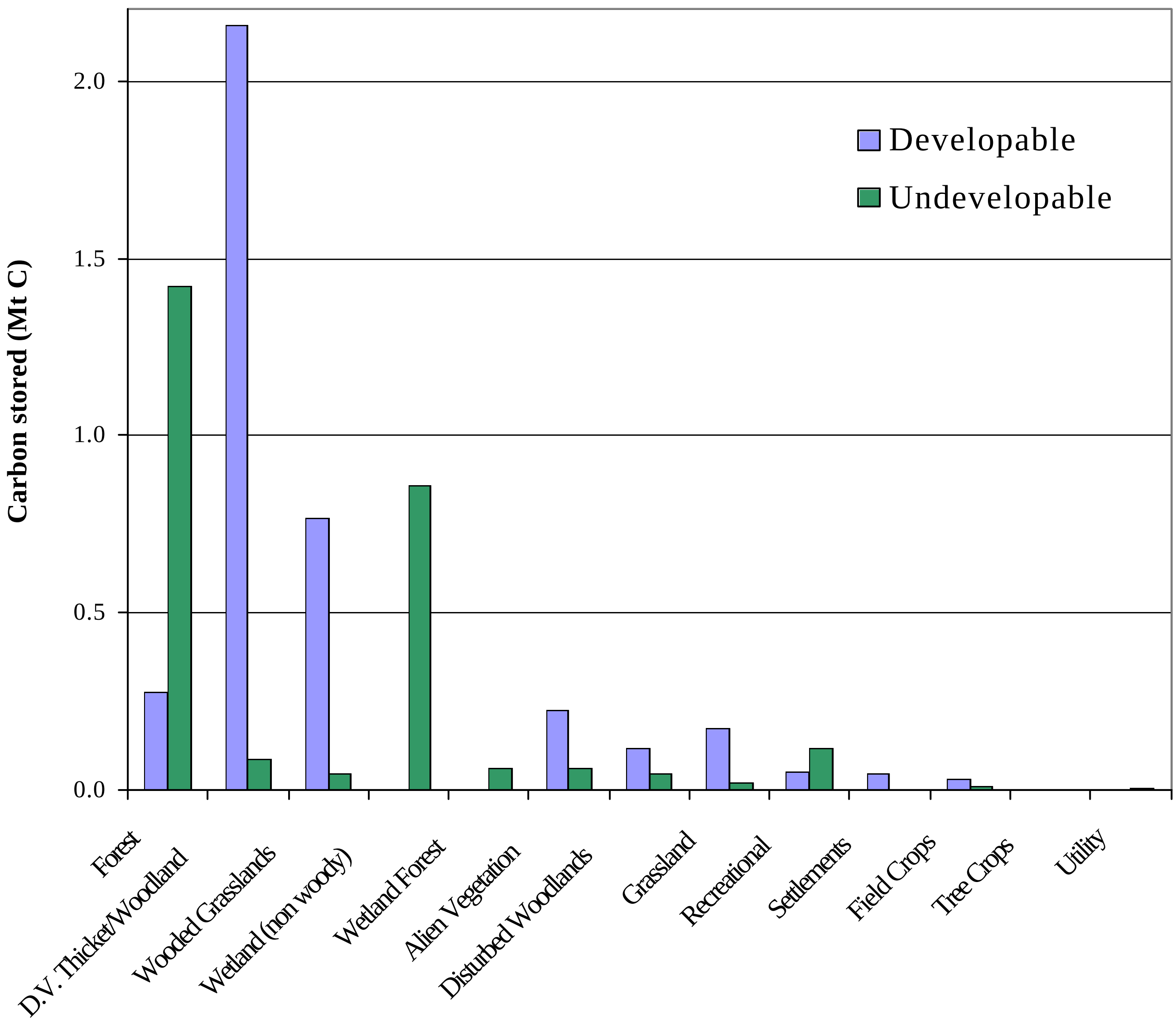


Table 18 EESMP land and carbon stock on developable and undevelopable land, 2005-6

Cover type	Developable				Undevelopable			
	Area (ha)	% of cover	Carbon (tC)	s.e.	Area (ha)	% of cover	Carbon (tC)	s.e.
D.V.T./ Woodland	17,870	96%	2,157,904	152,748	740	4%	89,405	6,329
Wooded Grasslands	10,721	94%	765,623	51,279	671	6%	49,455	3,752
Unspecified	*6,885*	*95%*	*455,152*	*35,288*	*341*	*5%*	*22,539*	*1,747*
Bushclump Mosaic	*362*	*100%*	*23,932*	*1,855*	*0*	*0%*	*17*	*1*
Acacia Savanna	*3,474*	*92%*	*286,539*	*37,161*	*310*	*8%*	*25,592*	*3,319*
Protea Woodland	*0*	*0%*	*0*	*0*	*12*	*100%*	*807*	*63*
Faurea Woodland	*0*	*0%*	*0*	*0*	*8*	*100%*	*499*	*39*
Forest	2,673	25%	276,103	47,496	7,974	75%	1,421,989	76,986
Coastal Scarp Forest	*0*	*0%*	*0*	*0*	*4,683*	*100%*	*931,226*	*75,321*
Transitional Forest	*2,673*	*87%*	*276,103*	*47,496*	*400*	*13%*	*41,281*	*7,101*
Coastal Lowland Forest	*0*	*0%*	*0*	*0*	*989*	*100%*	*164,439*	*10,388*
Dune Scrub and Forest	*0*	*0%*	*0*	*0*	*925*	*100%*	*123,483*	*7,324*
Riverine Forest	*0*	*0%*	*0*	*0*	*833*	*100%*	*137,830*	*6,362*
Unspecified	*0*	*0%*	*0*	*0*	*143*	*100%*	*23,730*	*1,095*
Wetland (non woody)	0	0%	0	0	5,706	100%	858,767	117,055
Floodplains	*0*	*0%*	*0*	*0*	*96*	*100%*	*23,532*	*5,894*
Freshwater Wetland	*0*	*0%*	*0*	*0*	*4,988*	*100%*	*742,708*	*116,010*
Estuarine Wetland	*0*	*0%*	*0*	*0*	*621*	*100%*	*92,527*	*14,453*
Alien Vegetation	2,958	78%	226,374	14,388	829	22%	64,840	3,263
Alien Thicket	*1,606*	*82%*	*84,987*	*7,417*	*358*	*18%*	*18,936*	*1,653*
Alien Woodland	*780*	*67%*	*72,141*	*4,580*	*389*	*33%*	*35,941*	*2,282*
Feral Plantation	*571*	*87%*	*69,247*	*11,447*	*82*	*13%*	*9,962*	*1,647*
Grassland	2,504	88%	175,860	28,468	351	12%	24,674	4,014
Secondary Grassland	*46*	*100%*	*2,925*	*212*	*0*	*0%*	*0*	*0*
Primary Grassland	*801*	*87%*	*49,477*	*5,866*	*118*	*13%*	*7,303*	*866*
Not Applicable	*1,656*	*88%*	*123,458*	*27,856*	*233*	*12%*	*17,371*	*3,919*
Disturbed Woodlands	2,007	71%	119,276	28,950	826	29%	49,061	11,908
Recreational *(parks)*	535	31%	54,476	132	1,174	69%	119,457	289
Wetland Forest	0	0%	83	13	207	100%	65,424	3,944
Swamp Forest	*0*	*0%*	*0*	*0*	*85*	*100%*	*24,218*	*2,966*
Mangrove Forest	*0*	*0%*	*0*	*0*	*56*	*100%*	*21,115*	*1,036*
Not Applicable	*0*	*1%*	*83*	*13*	*43*	*99%*	*12,871*	*2,087*
Barringtonia racemosa	*0*	*0%*	*0*	*0*	*24*	*100%*	*7,097*	*1,151*
Hibiscus tiliaceus	*0*	*0%*	*0*	*0*	*0*	*100%*	*123*	*20*
Settlements (rural)	*790*	*98%*	46,934	11,392	14	2%	813	197
Field Crops	507	68%	31,993	5,751	234	32%	10,064	1,134
Fallow Crop Lands	*371*	*91%*	*26,892*	*5,706*	*38*	*9%*	*2,731*	*579*
Commercial Gardening	*92*	*46%*	*3,443*	*644*	*107*	*54%*	*4,018*	*752*
Large Scale Commercial	*44*	*33%*	*1,658*	*310*	*89*	*67%*	*3,314*	*620*
Tree Crops	14	100%	1,422	237	0	0%	0	0
Plantations	*10*	*100%*	*835*	*206*	*0*	*0%*	*0*	*0*
Fruit Trees	*4*	*100%*	*587*	*117*	*0*	*0%*	*0*	*0*
Utility	5	6%	242	3	88	94%	8,707	21
Cemetery	*0*	*0%*	*0*	*0*	*84*	*100%*	*8,523*	*21*
Grassed Road Verge	*0*	*0%*	*0*	*0*	*4*	*100%*	*184*	*2*
Grassed Reservoir	*5*	*100%*	*242*	*3*	*0*	*0%*	*0*	*0*
TOTAL (Mt C)			**3.86**	**0.17**			**2.76**	**0.14**

While EESMP classified land receives special attention when developments are proposed, there is potential for some of this area to be converted to less carbon rich cover types. If, for example, all of the vulnerable area were converted from their current carbon densities to a land cover type with the carbon density of a tilled agricultural field on sandy soil (37 tC/ha, IPCC 1996), 2.3 Mt C or 8.6 Mt CO_2 could be emitted. If the same calculation is done assuming transformation to secondary grassland (using 61 tC/ha from the geology weighted secondary grassland) losses would be 1.4 Mt C or 8.6 Mt CO_2 (*Appendix L*). Albeit, if a low carbon storage cover type, like Alien Thicket, is developed such that part of the land has structures on it but the remainder is restored grassland or forest, there is potential for some developments to increase stocks.

The EMD has several mechanisms to try to protect the vulnerable the open space system, and therefore its carbon stock, through negotiations with landholders and developers. The 53.5 ha of land secured in environmental servitudes agreed upon by 2005, most of which was forest and grassland, ensured 6,000 ±450 tC of the carbon stock (*Appendix M*). The 222 ha purchased by the municipality through the EMD (or is in the process of purchase), constituted 18,100 ±700 tC of secured storage (*Appendix M*). While these constitute a relatively small percentage of the vulnerable carbon stock, these sort of carbon emission offsets are within the range of fundable small-scale reforestation projects.

3.10 Regeneration modeling

The Century model was successfully calibrated for most of the sampled EMA woody ecosystems. The model was run using the representative species lignin content, soil texture, and climate data inputs for each cover class (*Appendix N*) predicting aboveground biomass on an annual basis such that the ecosystem processes modeled reached an equilibrium biomass density equal to the ABG density sampled in the field. For all classes the model was allowed to make AGB predictions over a sample of 2000 years to ensure equilibrium had been reached (*Figure 9*) after which a hypothetical disturbance and climate changes were introduced. Using the model as calibrated for the particular cover class, regeneration of biomass was modeled over 50 years post disturbance (*Figure 10*) and used to estimate aboveground biomass carbon accumulation rates over this period (*Table 19*). While growth rates were predicted annually, 5 year averages are presented here to smooth fluctuations and because the CDM requires monitoring at 5 year intervals.

Equilibrium AGB values reached were very similar to those sampled in the field for all the indigenous forest classes, Transitional Forest, Feral Plantation, Alien Woodland, Wooded Grassland, and Bushclump Grassland Mosaic (*Table 19*). Ipithi Reserve, being at an early growth stage, was excluded from the Transitional Forest class. Calibration failed for Alien Thicket and Disturbed Woodland: given the soil, lignin, and climate data for these classes, the model could not reach equilibrium at the sampled AGB density. Instead model runs continued accumulating biomass reaching 80-100 tons/ha (40-50 tC/ha), close to forest and Dry Valley Thicket values (Knowles, 2006). This suggests it is possible for these systems to attain forest-like biomass densities in the next 30-40 years. The other 'disturbed' classes, Transitional Forest, Feral Plantation, and Alien Woodland, were able to calibrate, indicating that these classes may have achieved relatively steady biomass densities for their current conditions.

Adding predicted temperature, precipation, and CO_2 changes associated with the IPCC emissions scenarios resulted in marginal sequestration in some cover types (*Table 19*). Changes predicted using the CSIRO GCM results were smaller than those from CCSR across vegetation types. To show the range of results, data with the smallest changes, CSIRO for the B1 scenario, and those with greatest changes, CCRS A2, were presented. Under the more extreme emissions scenario, A2, Coastal Lowland Forest, Dune Forest, Transitional Forest, Dry Valley Thicket, and Coastal Bushclump Grassland Mosaic areas are likely to accumulate extra biomass at rates under 0.1 tC/ha/yr over at least 50 years. The more open of these cover types, Transitional Forest and Coastal Bushclump appeared to accumulate biomass more quickly in the first 20 years of the change and also showed some accumulation in the low emissions scenario, B1. The forest types increased growth rates more slowly as the climate changes became more extreme and showed no significant growth in the B1 scenario.

Figure 9 Century model run for 2000 years to calibrate to the average aboveground biomass of Coastal Lowland Forest (Knowles, 2006).

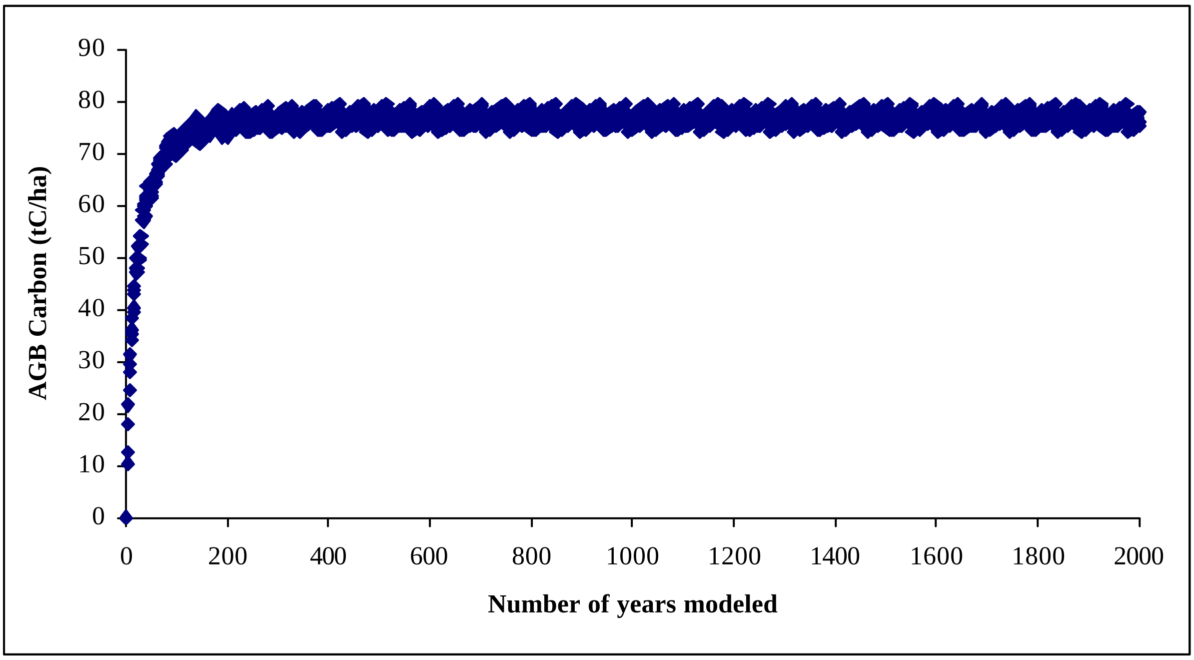


Figure 10 Predicted post disturbance carbon accumulation for modeled Coastal Lowland Forest ecosystem (Knowles, 2007).

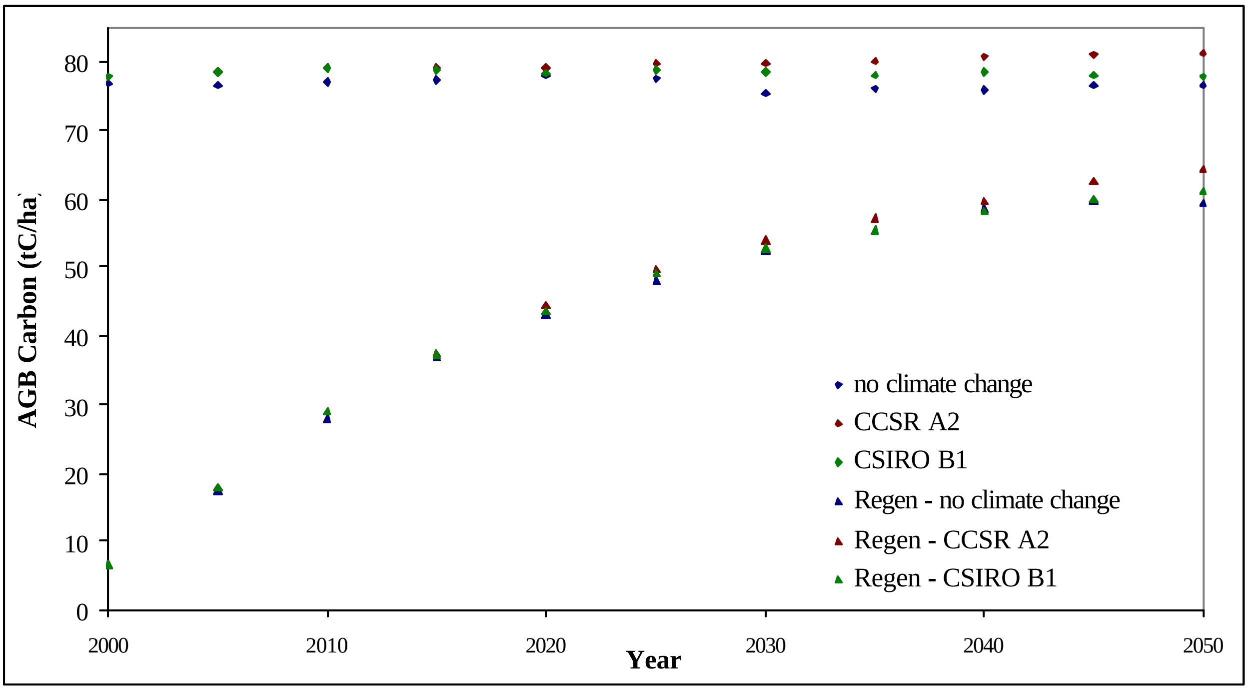


Table 19 Century Model results for EMA ecosystems: equilibrium states, climate change scenario and post-disturbance regeneration rates. (* rates in grey are *not* significantly different from no growth or 0 tC/ha/yr at a= 0.1) *5-year growth rates in Appendix N*

Cover type	Sample mean carbon density (tC/ha)	Model equilibrium carbon density (tC/ha)	Carbon accumulation rate (tC/ha/yr) *					
			no climate change		B1 CSIRO		A2 CCRS	
			20 yr mean	*50 yr mean*	20 yr mean	*50 yr mean*	20 yr mean	*50 yr mean*
Coastal Scarp Forest	66	66	0.05	*-0.01*	-0.05	*-0.04*	-0.01	*0.02*
Coastal Lowland Forest	75	77	0.06	*-0.01*	0.03	*0.00*	0.06	*0.07*
Dune Forest	40	42	0.03	*0.00*	0.01	*0.00*	0.03	*0.04*
Transitional Forest (excl. Iphithi)	27	27	0.03	*0.00*	0.06	*0.02*	0.08	*0.06*
Dry Valley Thicket/ Broadleaf Woodland	29	30	0.02	*-0.01*	0.00	*0.00*	0.03	*0.03*
Coastal Bushclump Mosaic	8	8	0.03	*0.00*	0.11	*0.03*	0.15	*0.08*
Wooded Grassland	5	5	-0.03	*0.00*	0.01	*-0.02*	0.01	*0.00*
Alien Woodland	14	15	0.00	*0.00*	-0.03	*-0.02*	-0.02	*0.00*
Feral Plantation	45	59	0.05	*0.00*	-0.02	*-0.03*	0.01	*0.03*

Cover type	Post disturbance carbon density (tC/ha)	Years to reach pre-disturbed carbon density	Post disturbance carbon accumulation rate (tC/ha/yr)					
			no climate change		B1 CSIRO		A2 CCRS	
			20 yr mean	*50 yr mean*	20 yr mean	*50 yr mean*	20 yr mean	*50 yr mean*
Coastal Scarp Forest	6	60-65	1.82	*0.97*	1.75	*0.95*	1.79	*1.01*
Coastal Lowland Forest	7	60-65	1.84	*1.06*	1.85	*1.09*	1.89	*1.15*
Dune Forest	5	55-60	1.36	*0.63*	1.34	*0.64*	1.37	*0.69*
Transitional Forest (excl. Iphithi)	3	35-55	1.02	*0.42*	1.06	*0.45*	1.08	*0.49*
Dry Valley Thicket/ Broadleaf Woodland	4	50-60	1.14	*0.46*	1.12	*0.48*	1.15	*0.51*
Coastal Bushclump Mosaic	3	30-50	0.15	*0.08*	0.21	*0.12*	0.22	*0.17*
Wooded Grassland	3	10-15	0.15	*0.06*	0.17	*0.06*	0.18	*0.08*
Alien Woodland	1	45-55	0.65	*0.23*	0.63	*0.25*	0.65	*0.27*
Feral Plantation	6	30-50	1.70	*0.89*	1.67	*0.91*	1.71	*0.97*

The addition of changing climate variables over time tended to increase post-disturbance growth rates over time for most cover classes compared to growth rates in the regeneration scenario that assumed no climate change. These increases were small (<0.1 tC/ha/yr more) and generally statistically insignificant (*Table 19, Appendix N*), with the exceptions of Coastal Lowland Forest and Transitional Forest, for which accumulation rates in the CCSR A2 scenario were significantly greater, and Coastal Bushclump Mosaic, for which all accumulation rates assuming climate change were significantly greater than the no climate change scenario.

Comparing post disturbance growth rates between classes, the indigenous forest classes, Dry Valley Thicket, and Feral Plantation had similar carbon accumulation rates for the first 5 years (2-2.3 tC/ha/yr, *Appendix N*). In all classes growth slowed over time, but Coastal Scarp and Lowland Forests and Feral Plantation maintained higher rates than other classes over the time interval, having higher mean 20 year accumulation rates (1.7-1.9 tC/ha) than Dune Forest (1.3-1.4 tC/ha) or Dry Valley Thicket (1.1-1.2 tC/ha). Coastal Scarp and Lowland Forest carbon accumulation plateaued at lower carbon densities relative to their pre-disturbance densities compared to other cover types, indicating these forests may have slow long-term accumulation beyond the 50 year time period.

The open woodland classes, Coastal Bushclump Grassland Mosaic and Wooded Grasslands, stored less carbon and had slower carbon accumulation rates (0.1-0.2 tC/ha/yr) than forests. However, because the biomass of all the woodland ecosystems was lower than forest, both these and the disturbed systems were able to return to their original carbon stock within 20-40 years rather than the 50-60 or more years needed for forest recovery. The Feral Plantation class acted pretty much as the other forests, but the other disturbed cover types for which the model was calibrated, Transitional Forest and Alien Woodland, behaved differently. Transitional Forest behaved similarly to Dry Valley Thicket while Alien Woodland accumulated biomass faster than indigenous open woodlands, but slower than forest and Dry Valley Thicket, and reached equilibrium in close to 15 years.

There is potential for woodlands and disturbed cover in the peri-urban and rural areas of the municipality that is not protected in nature reserves to supply local communities with resources such as fuelwood and building material. The mean 20 year growth rates here indicate that these ecosystems could maintain their biomass carbon stocks if annual harvesting is kept to 2-4% of the standing biomass or less because this amount will regrow in a year. With climate change, the regrowth rates, and therefore the sustainable harvesting rates, could be slightly greater.

3.11 Carbon budgeting

According to the eThewkini Municipality's *State of Energy Report 2006*, energy use in the EMA emitted 17.6 million tons of CO_2 annually, with 53% of emissions coming from industry, commerce, and agriculture and 26% from transport in 2005. More than half of the annual carbon emissions (54%) resulted from electricity use, rather than direct burning of fuels. Municipal electricity is predominantly produced in coal burning generators, one of the most carbon intensive means of generation. The EESMP has sequestered a net of 24.2 Mt CO_2 meaning that every 1.4 years the municipality emits as much carbon as is stored in all the vegetation and soil open space system. In other words the equivalent of the entire open space system carbon stock is burned every 1.4 years.

It is likely that the open space system carbon stock is growing and sequestering carbon, but extremely slowly compared to annual emissions. The following assumptions were made to make a conservative estimate of long term sequestration rates (*Table 20*):

- Most intact EESMP cover classes have reached an equilibrium, in which they are not accumulating more carbon than is released by decomposition. If an extreme climate change scenario (A2) is assumed some of these classes may sequester slowly over time as suggested by Century model results.
- Alien Thicket and Disturbed Woodland have not yet reached an equilibrium carbon density and will actively sequester carbon with or without climate change. The Century model would not calibrate for these two classes at their current biomass levels, but suggested that, based on their soils and climactic conditions, they may be on a growth trajectory toward biomasses similar to forest or Dry Valley Thicket. A growth rate between these two was applied.
- Transitional Forest class is defined as forest that has and areas of this cover class therefore growing and accumulating carbon regardless of climate change. It was assumed that on average the disturbances occurred some time ago and so the modeled 50 year growth rate was assumed.
- No area in the EESMP is lost or significantly degraded from its current state. Similarly no large areas are added or rehabilitated.

Based on these assumptions, the EESMP area sequesters roughly 31,000 – 36,000 tCO_2 annually, sinking about 0.2% of the current EMA emissions (*Table 20*). Some supposedly intact forests and woodlands may actually still be recovering from past disturbances. Century model results suggested that, if forests were damaged in the last 30-50 years, they may still be accumulating biomass and hence carbon. This also makes no assumptions about sequestration or losses in wetlands, the fate of which will be very much determined by localized conditions and particularly development in their individual catchments, perhaps more so than by gradual changes in climate.

Table 20 Conservative carbon sequestration scenarios for the open space system with and without assuming climate change

Cover class	Area (ha)	Carbon accumulation rate (tC/ha/yr) no climate change	Carbon accumulation rate (tC/ha/yr) CCSR A2 scenario	Annual accumulation (tC/yr) no climate change	Annual accumulation (tC/yr) CCSR A2 scenario
Coastal Lowland Forest	989	0.00	0.07	0	68
Dune Forest	925	0.00	0.04	0	40
Dry Valley Thicket	18,610	0.00	0.03	0	616
Coastal Bushclump Mosaic	3,785	0.00	0.08	0	308
Transitional Forest	3,072	0.42	0.49	1,290	1,505
Alien Thicket	1,964	1.49	1.52	2,927	2,986
Disturbed Woodlands	2,833	1.49	1.52	4,221	4,306
Annual carbon accumulation (tC/yr)				**8,438**	**9,829**
Annual CO2 sequestration (tCO2/yr)				**30,940**	**36,038**
EMA annual emissions (tCO2/yr) (EThekwini Municipality, 2006)				*17,859,000*	
% of EMA annual emissions sequestered				**0.17%**	**0.20%**

Carbon emissions for the municipality will increase under a business as usual scenario. Transport sector emissions are predicted to increase. Private car traffic is expected to increase 50% by 2050, while public transport is underutilized compared to capacity (eThekwini Municipality 2006). Electricity use has been rising with purchases increasing 3.2% from 2003/4 to 2004/5. Industrial activity and domestic energy use are likely to increase. Although many in eThekwini's peri-urban/rural areas produce domestic energy on site from biomass or liquid fuels, which are less carbon intensive than coal sourced electricity, due to health concerns and social equity factors, more of these areas are likely to receive electricity in future. Use of renewable energy has been almost nonexistent.

The vast majority of the municipality's high carbon density ecosystems lie in the EESMP. If this is protected it can be assumed that land cover change will not be a major source of emissions and may be a net sink, albeit a relatively small one. Sequestration in the open space will slow once disturbed ecosystems recover and reach equilibriums, however, rehabilitation efforts may enhance growth and put alien infested ecosystems onto more carbon rich indigenous ecosystem growth trajectories. Increasing future temperatures and CO_2 concentrations may facilitate plant growth, changing ecosystem equilibria to higher carbon densities; model results suggest this could increase sequestration rates by about 16%. Nevertheless sequestration rates will likely remain a small fraction of the EMA's large and growing emission rates.

Efforts to curb eThekwini's emissions include:

- plans to upgrade municipal public transport for 2010's FIFA World Cup
- the National Energy Efficiency Strategy (NEES)
- the EMD's future work to facilitate development and implementation of a local energy efficiency strategy and action plan as informed by the State of Energy Report and NEES.

These efforts will slow the increase of Municipal emissions rates but are unlikely to get them below current rates. For example, NEES sets national sectoral energy efficiency targets for percentage reductions over predicted use growth rates, to be achieved by 2015. Sectoral energy reduction targets have been set at: 15% for industry and commerce, 15% for public buildings, 9% for transport, and 10% for domestic households (DME, 2005). Applying these targets to eThekwini's usage would result in an 11% reduction in annual energy use and a 2.2 Mt CO_2 reduction in annual emissions over forecasted increases by 2015 (eThekwini Municipality 2006).

4 Discussion

4.1 Management suggestions

The results of this carbon inventory can be used to inform future management of the EESMP to ensure maintenance and, where possible, growth of the EMA carbon stocks. This will consist of:

- *Continuing eThekwini Municipality's efforts to protect the EESMP, from both loss of open space area and from disturbance of open space ecosystems, as the city develops*

Fortunately the highest carbon density land covers, indigenous forest and wetlands, are largely by NEMA EIA regulations, the National Forest Act, and the National Water Act, but there are cases in which these cover types are damaged or removed in development. For example, small wetlands in the EMA may not have been mapped in the EESMP and therefore might not receive ample protection. In addition, developments within the watershed of a wetland, but not actually on the wetland itself, may change the hydrology of the area and cause drying which would result in the loss of deep soil carbon stocks, a significant part of the EESMP carbon stock.

Much of the EESMP carbon stock is on other cover classes that are not necessarily protected from development (58% of the stock), particularly in Dry Valley Thicket/Broadleaf Woodland which has a relatively high carbon density. This cover type is found in the outer west area of the EMA, which is being considered for industrial expansion and residential development. Controlling densities and selection of development sites in this area can minimize land use change carbon emissions. In addition, many of the ecosystems that are not formally protected provide resources such as fuelwood, building material, and medicines to impoverished communities. As populations grow it may become necessary to establish community management plans, including measures such as replanting, limiting harvests, and possibly planting dedicated woodlots on some part of the land, to prevent these areas from becoming degraded, losing carbon stock, and losing their ability to continuously supply these resources.

- *Promoting restoration of damaged and alien infested ecosystems*

It was found that cover types such as Alien Thicket and Disturbed Woodland had lower mean carbon densities than all other cover types (including grasslands), and were statistically different from other woodland and forest types. The other damaged ecosystem classifications. Alien Woodland, Feral Plantation, and Transitional Forest, had greater tree biomass carbon stocks and carbon densities (similar to Dry Valley Thicket), but still had lower carbon densities than other forest types. This indicates that if these areas were to be restored to intact indigenous ecosystems there will likely be no net loss of carbon stock and it is possible that stocks could increase if these areas support significantly greater carbon density cover types. It is important to note that the initial efforts of restoration, such as alien plant removal, can cause an initial release of carbon, but as indigenous vegetation grows it will sequester carbon and enrich soils. Thus the carbon budgeting of restoration activity must include several decades of growth.

- *Ensuring that where developments do occur in the open space system, that carbon stock losses are minimized*

It is unlikely that the entire mapped area of the EESMP will remain as open space in the future, however, careful management of developments can minimize carbon losses and in some cases could increase carbon stocks. Currently developments approved in the open space system are required to submit **Environmental Management Plans (EMPs)**. Often EMPs require maintenance and/or restoration of portions of the land in question that are to be left free of development, which will help maintain and could augment carbon stock on these sections. In addition, steps to minimize building emissions and increase the resulting carbon stock on portions to be developed could be included, such preservation or relocation of topsoil and tree planting on the premises.

- *Taking climate change impacts predicted for the municipality into account when prioritizing land for protection.*

Climate change is predicted to increase temperatures and change rainfall patterns in the EMA (CSIR, 2006). This will likely change the spatial ranges of species and ecosystems in the open space system. Although mean annual rainfall isn't predicted to change notably, it is likely to fall more erratically and be concentrated into intense rainfall events. The soils of the EMA are predominantly sandy and are therefore unlikely to hold moisture well, especially given higher temperatures accelerating evaporation. This change in rainfall distribution will effectively be a drying for many ecosystems. While most the ecosystems in the EMA occurred in overlapping ranges, high carbon density indigenous forests and wetlands generally occurred in areas with higher rainfall than the low carbon density woodlands on average. Grasslands were also located in higher rainfall areas with higher altitudes. Areas within the EMA that receive the most rainfall should be prioritized for conservation because, if they are at the top of an ecosystem's rainfall range currently, they may be the only places remaining within that range under a drier climate scenario. Ecosystems damaged by floods and droughts may also be more vulnerable to alien species invasion, highlighting the importance of current alien species management.

Sea level rise is another impact of climate change that will affect the EMA. This will threaten Dune Forest and Estuarine Wetlands in particular. With high coastal development pressures, little of these ecosystems remain, and much of what is left is sandwiched between developed areas and the sea. As the sea level rises, there will be no way for these ecosystems to retreat and they will likely lose significant area to sea level rise and/or be damaged by high water and storms. Dune Forest was seen to have the slowest post disturbance carbon recovery rates of all forest types (*Table 19*). Not only do these systems store significant amounts of carbon and protect biodiversity, but they also stabilize beaches and river mouths from erosion, particularly important in light of potential increased flooding and storms. These areas will need special protection and buffer zones where possible.

- *Developing a targeted public education campaign about the causes and impacts of climate change, highlighting the role of the EESMP in mitigation and adaptation.*

Public education about climate change impacts and the role of the open space system in both mitigation and adaptation, particularly addressed towards planners, developers, and land holders, may assist the municipality in achieving its management goals for the open space system. It may make developers more willing to place environmental servitudes on their properties or actively engage in their EMPs. It will also help planners make better decisions about density limits and zoning on currently developable areas.

4.2 Carbon emission offset project potential

There is some potential for establishing land cover based carbon emission offset projects in the municipality's open space system, but these will likely have to be small-scale projects and/or make use of the voluntary markets to receive carbon market funding. For the first commitment period of the Kyoto Protocol (2008-2012), developed nations (Annex I nations) are *only* permitted to receive Certified Emission Reductions (CERs) credits via the

Clean Development Mechanism (CDM) from afforestation and reforestation (A/R) activities in the land cover sector. Afforestation, defined as foresting areas not previously forested, will not be considered here as planting trees on areas that would otherwise naturally support indigenous woodland, wetland, or grassland as this would negate the biodiversity conservation function of the EESMP and ignore important ecosystem services and habitat provided by non-forest cover types. Avoiding deforestation and other ecosystem destruction that may otherwise occur under development pressure is not currently considered for CDM projects; however, there have been discussions of receiving credit for avoided deforestation in future Kyoto commitment periods and these sorts of projects have been funded through the voluntary carbon market.

a Rehabilitation and reforestation potential

The area available for reforestation in the open space system is limited and opportunities to increase the size of the open space system over and above the current EESMP are limited by the municipality's growing population, housing backlog, and economic growth priorities. However, there are some disturbed ecosystems within the current EESMP that could be rehabilitated, likely increasing carbon stocks.

Not all habitat restoration would be well suited to carbon offset trading. Restoration of Secondary Grasslands and Transitional Forest would entail protection from disturbance and management activities like alien removal and grassland burning, but not include tree planting. Feral Plantations in the open space system could be rehabilitated, involving alien removal, followed by tree planting if the region is to be converted to a wooded indigenous cover type. The calculations of the initial stock loss in the clearing followed by the carbon storage gain in regeneration will significantly complicate the carbon accounting. This is not to discount this as a useful endeavor, but the complexity may make it a less attractive project if competing for international funding, and may not count as 'reforestation' if the original cover type is viewed as 'forest' by virtue of its closed tree canopy.

The EESMP held roughly 6,700 hectares of Alien Thicket, Alien Woodland, Disturbed Woodland, Fallow Fields, and other Agricultural Fields in 2005 that could potentially be rehabilitated (*Table 1*) using tree-planting activities, again depending on the desired resulting cover type. Inventory results indicated that rehabilitation of these ecosystems would likely be carbon storing, or at least carbon neutral, but the applicability of these activities for carbon trading under Kyoto is limited by CDM policy. For land to be considered for reforestation CDM projects, it must have been deforested before 1990. Furthermore, the definition of 'reforestation' depends upon the definition of 'forest.' Kyoto allows nations to chose their own **forest definition** to be adopted by their CDM Designated National Authorities (DNA) by selecting a minimum tree canopy cover between 10-30% and a minimum canopy height between 2-5m for an area to be considered forest. A workshop held by the DNA in Pretoria in September 2006 suggested a definition of 30% canopy cover and 2m minimum height, although this had yet be registered with the CDM executive board (DME, 2006).

Using a threshold of 30% means that rehabilitation will be deemed 'reforestation' if the resulting restored cover type has greater than 30% cover. This would apply for areas with less than 30% cover being restored to indigenous forest or Dry Valley Thicket. Preliminary canopy mapping indicated that intact Coastal Bushclump Woodland and other Wooded Grassland naturally had canopy covers below 20%, and thus rehabilitation to these types would not likely count as 'reforestation' (*Table 7*). However, if a low canopy cover limit had been selected (10%), it is likely that most of the area available for rehabilitation would be considered forested already. For example, Disturbed Woodlands assessed with aerial photography already had a mean canopy cover of 35%.

Table 21 Hypothetical reforestation of disturbed cover classes to achieve carbon densities of either intact Dry Valley Thicket/Broadleaf Woodland (DVT) or Coastal Scarp Forest (CSF)

* AGB carbon densities: DVT = 29 tC/ha, CSF = 66 tC/ha,
** Assumed carbon accumulation rates: DVT = 1.1 tC/ha/yr – 20yr rate, CSF = 1.1 tC/ha/yr – 50yr rate used as forest regeneration will take longer than 20 years (Knowles, 2006)

EESMP General Description *(Detailed subclasses)*	**Total area (ha)**	**Ave. patch area (ha)**	**Carbon density (tC/ha)**			**Rehabilitation carbon stock change (tC)**			
			Orig.	***Change to DVT****	***Change to CSF****	**Total to DVT**	**Total to CSF**	**Patch to DVT**	**Patch to CSF**
Alien Thicket	*1,964*	*9.5*	9	*20*	*57*	39,661	111,389	500	538
Alien Woodland	*1,169*	*10.0*	14	*15*	*51*	17,178	59,875	733	512
Disturbed Woodlands	2,833	*17.5*	9	*20*	*56*	56,442	159,879	512	987
Fallow Crop Lands	*409*	*14.1*	5	*24*	*61*	9,806	24,726	338	853
Commercial Market Gardening	*199*	*6.9*	5	*24*	*61*	4,788	12,072	165	416
Large Scale Commercial	*133*	*7.4*	5	*24*	*61*	3,191	8,046	177	447
TOTAL	**6,707**					**131,067**	**375,986**		

EESMP General Description *(Detailed subclasses)*	**Years to new carbon density****		**Annual storage for total cover area****		**Annual storage for average patch****	
	DVT	**CSF**	**tC/yr**	**tCO_2/yr**	**tC/yr**	**tCO_2/yr**
Alien Thicket	18	52	2,161	7,923	10	38
Alien Woodland	13	47	1,286	4,716	11	40
Disturbed Woodlands	18	51	3,116	11,425	19	71
Fallow Crop Lands	22	55	449	1,648	15	57
Commercial Market Gardening	22	55	219	805	8	28
Large Scale Commercial	22	55	146	536	8	30
TOTAL			**7,378**	**27,053**		

Tree canopy cover and cover change for 1990-2005 have not been mapped for the EESMP area, making it difficult to assess the area actually available. In addition, landowners of private plots may chose not to implement reforestation projects. Nevertheless, as a hypothetical case, if all of these open canopy disturbed cover areas (6,700 ha) could be restored to indigenous cover with carbon densities between that of Dry Valley Thicket, on the lower end of what might be considered 'forest,' and Coastal Scarp Forest, on the high end of forest carbon density, an additional 0.13 to 0.38 Mt C could be sequestered in the EESMP over roughly 20-50 years of regeneration (*Table 21*). This is a conservative estimate as it does not take into account increases in soil carbon that would likely accompany rehabilitation.

It is unlikely that all of this area is indeed available and projects may occur on a landholder by landholder basis. The average habitat patch size was calculated for each cover type and the carbon gains of restoring an average patch was assessed for each type (*Table 21*). Rehabilitation of single landholder units would not sequester enough carbon to be funded individually, but many patches could be bundled to create a project that would sequester less than 8,000 t CO_2 per year and qualify for simplified small-scale CDM methodologies.

Inline with the sustainable development goals of the CDM, reforestation projects provide job creation opportunities, not just through short term planting work, but in long term maintenance and monitoring programs needed to achieve and prove real carbon benefits. Where available, carbon trading funds can be used to maintain these livelihoods. An estimated 55,000 households use fuelwood for heating, 18,000 of which also use fuelwood for cooking (eThekwini Municipality 2006). Tree planting combined with sustainable harvest plans, could produce both increased carbon stocks and a sustained flow of forest products to communities that rely on them. EThekwini Municipality's **Working for Ecosystems** project, in which funding is directed at stakeholder-driven, job-creating, ecosystem rehabilitation and management activities, provides an ideal opportunities to pilot some of these activities. In addition restoration activities required of developers in their **EMPs** also provide avenues to implement these rehabilitation measures.

While some of these activities have been initiated or requested on a piece-meal basis already, it would be possible to prove additionality because rehabilitation is not a business as usual activity. It currently occurs where special project funding is applied, such as Working for Water or Working for Ecosystems. Although rehabilitation is requested by the EMD in EMPs as a standard practice, policy compliance can be considered additional in the CDM if the policy arose post November 2001 (UNFCCC 2006) and/or the policy is not widely adhered to. Larger scale rehabilitation is not generally practiced or is limited by funding and so would likely qualify for tradable offset credits.

b Avoided ecosystem losses and damage

Although the CDM currently does not consider avoided deforestation, voluntary markets have considered such project viable and its inclusion in Kyoto policy post 2012 was discussed at 2006 COP meeting, although a consensus on mechanism was not reached (UNFCC, 2006). As discussed above, an added focus should be on areas not currently protected, but with increasing development pressure and fairly high carbon densities such as Dry Valley Thicket. Applications to develop on these areas would serve as ample proof of additionality. While environmental servitudes are currently being requested as a matter of course by the EMD, the addition of possible carbon funding for avoided carbon losses could incentivize land holders and developers to:

- agree to servitudes they may have rejected otherwise
- declare servitudes on high carbon density areas and move their intended development to lower carbon density areas
- better uphold, rehabilitate, manage, and monitor their servitude land and follow EMPs to prove carbon stocks have indeed been preserved, or increased where possible, over time as a condition for receiving credit funds

The municipality itself could also use carbon based funding for purchase and managements of carbon rich lands that are being proposed for development in cases where landholders refuse servitudes and EMPs.

4.3 Suggestions for further research

The current carbon stock inventory of the open space system produced reasonable and conservative carbon density and carbon stock figures to illuminate strategic management directions and project possibilities. However, further research would assist management of the open space system to maintain its integrity during predicted climate changes in the EMA. In addition, site based and/or more detailed ecosystem research would be needed to initiate for the accounting in a tradable carbon emission offset project. Such research directions include:

- *EESMP mapping:*
  - Canopy cover mapping within the open space system would assist in identifying potential CDM-A/R project areas based on South Africa's DNA approved forest definition. This could be done relatively simply using remote sensing software and current georeferenced aerial photography.
  - Historical disturbance mapping would also be needed to determine if areas to be restored meet the requirement of having lost forest cover pre-1990. Given georeferenced aerial photography or remote sensing images this would not be too onerous, but if these were not available it is suggested this be done on a site by site basis using the municipal hardcopy aerial photography archives.
  - More detailed classification of disturbed cover classes. Transitional Forest, Disturbed Woodland, and Alien Vegetation encompassed a wide range of structures resulting from different land use histories, making it difficult to generalize about their carbon densities. The above two mapping activities would assist in this regard. In addition assessing the likely cover type that would be achieved if an area were restored or allowed to regenerate would be a useful disturbed class descriptor. The reason to do this over the whole EESMP would be to refine total stock estimates, however, this activity could be reserved for potential project sites only if the current accuracy of the total carbon stock estimate is deemed sufficient.
  - Wetlands are high carbon density cover types that are very sensitive to disturbances both in and around them and reliable maps of their locations would aid in their protection. Currently not all wetlands in the EMA are mapped in the EESMP system and those that are were mapped using visual cues on aerial photography rather than field sampling.

- *Ecosystem reactions to climate change:*
  - As temperature and water availabilities change, it is likely that the distribution of cover types throughout the EESMP will change. Doing more detailed research on the abiotic ranges of various ecosystems in the EMA will assist forecasting future cover and would also help identify the cover types that disturbed and alien ecosystems be restored to. Predicting future cover distributions will help prioritize protection of refuge areas for ecosystems that will lose much of their range in the EMA. Rainfall, altitude, and geological ranges were examined here and significant overlaps were seen between classes; however temperature and actual water availability ranges (combining rainfall, evaporation, soil type, slope, proximity to rivers, etc) would need to be assessed and then combined with spatial climate scenarios for these variables.

- In addition to a change in cover types, climate change effects will likely also cause a change in productivity, hence carbon storage, within these cover types. These reactions were roughly modeled using the Century model for forest and woodland habitats, indicating a slight increase in sequestration by some ecosystems. Estimates could be refined with finer spatial data on predicted changes and more sampling along abiotic gradients within cover types. Carbon cofactor analyses were attempted here for exploratory purposes, but the sample was not adequately distributed to reliably test relationships. Increasing altitude did appear to increase forest carbon density. If the increasing altitude effect was actually a proxy for lower temperature or higher rainfall, this may not bode well for maintaining high carbon densities.

- *Carbon monitoring of current restoration activities:*
  - There is a limited range of alien removal and rehabilitation activities already ongoing in the municipality. For example, Ipithi Reserve was recently cleared of its Feral Plantation cover and now contains many indigenous tree samplings. This study used snapshot data to estimate rehabilitation gains by modeling and space-time substitution (assuming a cover type in one location could grow in to another), but it would be useful to monitor the changes in carbon storage in these projects over time and costs associated with achieving these to better assess the feasibility of using emission offset funding to finance future projects.

- *Resource harvesting practices:*
  - Century modeling indicated that sustainable biomass harvesting rates for most of the ecosystems found in the peri-urban/rural areas of the EMA are 2-4% of the standing biomass per annum. Site specific surveys about fuelwood use and harvesting areas would help assess which areas of the EMA are being unsustainably harvested. In these areas, community projects that develop sustainable harvest plans, possibly with a tree planting component, would result in increased carbon stock.

- *Matrix management:*
  - Outside the EESMP, carbon is also stored in agricultural and suburban lawn and garden systems. Exploring current storage and potential increased sequestration in these areas could illuminate methods of increasing carbon stock in these areas. While the EMD has currently has less influence over these areas than within the EESMP, this could be shared effort with municipal Agricultural, Housing, and Architecture Departments. Results could also inform EMD education outreach and design of carbon conscious EMPs for developments.

5 Conclusions

EThekwini Municipality, and South Africa as a whole, will be hard hit by the local impacts of global climate change driven by rising emissions of greenhouse gases, and yet South Africa is a significant contributor to the problem, being the fourteenth greatest GHG-emitting nation in the world (World Resources Institute, 2006). In eThekwini Municipality, rising temperatures, rising sea levels, and changed rainfall patterns are predicted to be great hindrances to sustainable development in the municipality by:

- threatening agricultural production
- reducing dam recharge and water availability
- causing health problems
- damaging key infrastructure
- altering the remaining natural ecosystems and the services they provide (CSIR 2006).

However, eThekwini Municipality has the advantage of an established and politically supported open space system as the eThekwini Environmental Services Management Plan (EESMP). This open space system provides *both* climate change mitigation and adaptation services:

- *mitigation:* open space system ecosystems store carbon in their soils and biomass, that would be released into the atmosphere if developed into low carbon density urban or agricultural cover types
- *adaptation*: the open space system provides ecosystem services, such as cooling and flood attenuation, that will become even more important in helping the city adapt to a warming climate with more punctuated rainfall.

Global land cover change, in the form of the loss of high carbon density ecosystems such as forests, has been for responsible for 20-30% if the anthropogenic driven increase in atmospheric GHG concentrations (Houghton, 1997). However, the efforts of the EMD to preserve the open space system in eThekwini Municipality will help ensure that this is not the case in the EMA. The eThekwini Municipality was estimated to emit 17.6 Mt CO_2 annually through its energy consumption (eThekwini Municipality, 2006). The 64,037 ha open space system was found to store 24.3 Mt CO_2. This means that every 1.4 years the EMA produces as much carbon dioxide as the net sequestration of the ecosystems in the open space system over their entire growth. Almost all emissions sources in the EMA are predicted to continue increasing, as electricity usage and traffic increase (eThekwini Municipality 2006), however if the municipality's remaining forest, woodland, wetland, and grassland, are protected in the EESMP, it is unlikely that land use change will be a major or increasing source of carbon emissions. Ecosystem modeling suggested the EESMP could potentially sink some additional carbon, even as the climate changes.

The eThekwini Municipality can take full advantage of the services the EESMP provides in terms of mitigating and adapting to climate change by:

- *Continuing, and improving, protection of the open space system*.

Currently as much as 58% of the EESMP carbon stock is on land that could potentially be developed in the future (*Table 18*). The EMD uses several tools to protect this land such as requesting environmental servitudes, environmental management plans, and municipal land purchase, but the possibility still exists for developments to displace ecosystems. Directed efforts should be made to ensure the protection of ecosystems found to have the highest carbon densities, such as forests, wetlands, and Dry Valley Thicket/Broadleaf Woodland (*Figure 5*). Part of ensuring that these ecosystems will maintain significant area in the EESMP over time will be researching how these ecosystems may react to local climactic changes. It may be possible to receive saleable carbon emissions offset credits for avoiding deforestation on the voluntary carbon market, and perhaps through the CDM in the next commitment periods of the Kyoto Protocol.

- *Enhancing open space carbon stocks through rehabilitation and sustainable resource use activities*

Opportunities exist to increase the amount of carbon stored in the EESMP through rehabilitation of disturbed ecosystems and related activities, such as establishing community woodlots or sustainable harvest plans. Such activities could not only store carbon, but could provide job creation and sustainable wood resources to dependent communities. Activities that include tree planting and reforestation could receive emission offset funding through CDM or through the voluntary market. The scale of sequestration opportunities is likely to be small (*Table 21*), but this may prove an advantage as small projects (<8,000 t CO_2 stored annually) qualify for simplified methodologies when participating in CDM.

Terrestrial carbon sequestration in the EMA will never be able to offset all of the city's GHG emissions, energy efficiency and renewable energy production are necessary climate change mitigation activities for the EMA and countrywide. However, the EESMP does hold significant carbon stocks that should be protected, so as not to add to emissions. In addition, projects that increase carbon stocks in EESMP could earn saleable emissions offset credits, the sales of which may make job-creating rehabilitation and reforestation projects financially viable. EThekwini Municipality would be the first in the country to implement such an initiative and could serve as model for other municipalities throughout Africa, demonstrating the advantages of protected open space systems for adapting and mitigating carbon emissions.

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