GREENING SOWETO: CALCULATING ABOVE-GROUND TREE BIOMASS, STORED CARBON AND NET ECONOMIC VALUE

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science (Environmental Science) in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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28th day of September, 2015 in Johannesburg

DEDICATION

This research report is dedicated to my son Yamikani Lembani and my wife Agness Nkonde Lembani for their moral support during the course of my study.

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This project wouldn’t have been completed without the endless support and guidance of my supervisor Professor Mary Scholes. I also want to thank her for the continued financial and material support.

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ABSTRACT

Quantifying ecosystem services of urban forests has become an important subject for the national and international ecological economics agenda. This is in the wake of offsetting anthropogenic emissions of CO_2, while promoting urban habitability and sustainability. This study estimates above-ground tree biomass, carbon stored and the associated economic value and net economic value of carbon sequestrated by the tree planting project in Soweto, Johannesburg, South Africa. Measurements of diameter at breast height (1.3 m) and tree height were done on all the individual trees that were recently planted (estimated to be about seven years) and other trees estimated to be over 25 years old in Petrus Molefe Park and Thokoza Park. A general allometric equation by Tietema (1993) was used to estimate above-ground biomass which was converted to carbon stocks. The economic value of carbon sequestrated was calculated at an equivalent price of R440.40 per tonne of carbon.

The total above-ground biomass, carbon stored and economic value, and net economic value of the trees in Petrus Molefe Park was 7.45 tonnes, 3.35 tonnes, R1,475 and R-495,325, while the trees in Thokoza Park had 205.76 tonnes, 92.59 tonnes, R40,777 and R-312,023, respectively. The results indicated that the older trees in Thokoza Park had larger amounts of above-ground tree biomass, greater carbon storage and net economic value than the younger trees in Petrus Molefe Park. The economic values of carbon sequestrated were less than the cost of planting the trees, therefore the net economic value of carbon sequestrated were negative. The project is at an early, but promising stage, since the Greening Soweto Project provided a number of ecosystem services (i.e. beautifying the landscape, filtering air, recreation and amenity etc.), the performance of the project was evaluated by the extent to which it integrates the environmental and social benefits into the economic benefits and opportunities.

Key words: Above-ground biomass, allometric equation, carbon stored, diameter at breast height, net economic value.

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CHAPTER ONE

1. Introduction

Urban regions or areas cover only approximately 10.2% of the world's terrestrial surface, nevertheless, more than 54% of the world's population live in urban areas (United Nations Department of Economic and Social Affairs 2014; McGranahan *et al*., 2005). Due to political and economic factors, it is predicted that by the year 2050 more than 66% of the global human population will be residing in urban areas (Montgomery, 2008; United Nations Habitat 2006). However, the massive backlog in improving urban infrastructure is critical in demonstrating environmental justice and urban habitability in developing countries. Exacerbated by the concerns of global climate change attributed to anthropogenic burning of fossil fuel and land use change, there have been a number of approaches used to enhance urban habitability, while ameliorating the adverse effects of greenhouse gases such as emission abatement, emission avoidance and carbon sequestration. Carbon sequestration is the capture and changing of atmospheric CO_2 into various forms of carbon that are not detrimental to the environment and do not contribute to climate change (Johnson and Coburn, 2010; Lal, 2007). In addition to numerous ecosystem services such as filtering dust and improvement of air quality, biodiversity conservation, providing shade and lessening storm water run-off, recent regional and international focus has been on urban greening to aid terrestrial carbon sequestration and urban sustainability (Stoffberg *et al*., 2010).

Urban trees or urban greening have significant potential to mitigate the net effects of global warming and climate change. Through the process of photosynthesis, trees absorb and convert atmospheric CO_2 and water into glucose and organic compounds using energy from the sun (Lal, 2007). Some of the organic compounds form structural tree tissues, whereas some CO_2 is re-released to the atmosphere through autotrophic respiration. Trees are perceived to be important net carbon sinks because they accumulate carbon in relatively long-lived tree biomass. A sink is any activity, mechanism or process that removes greenhouse gas from the atmosphere. Thus, trees at an optimum carbon sequestration age absorb more CO_2 through photosynthesis than is respired (Verweij *et al*., 2011; Peichl and Arain, 2006). This natural ability of trees to fix carbon dioxide underpins this study.

Numerous studies suggest that, previous failure to attach economic values to the ecological services of forests (traditional forests and urban forests) has been one of the causes of land use change and unsustainable management of forests (Chee, 2004; Howarth and Farber, 2002; Herendeen, 1998). Henceforth, it is important to fully understand the economic value of trees and also to enable all stakeholders to become conscious of the need to conserve trees since they provide ecological, social and economic benefits. As a result, estimating trees biomass, carbon stored and the economic value of urban trees is valuable in supporting the green economy. This is because developing countries are orienting their economies towards a green economy or low-carbon economy through integration of sustainable development (Nicholls and Vermaak, 2015; Kaggwa *et al*., 2013).

Even though carbon storage in trees is segmented into two (above-ground biomass and below-ground biomass), this study only focused on above-ground biomass. Above-ground biomass is the easiest to measure and the most relevant in planning and management of urban trees. Conventionally, tree biomass is determined through destructive sampling procedures in which the species of interest are harvested, dried to reduce the moisture content and weighed for dry biomass (FAO and CIRAD Online 2014). However, total harvesting of the trees for estimating tree biomass is environmentally, economically and politically restrictive. As a result, urban trees are generally protected and cannot be destructively sampled.

Given the restrictions mentioned above, the current study employed an easy and non-destructive method of measuring urban tree above-ground biomass and calculating carbon stored and the economic value by using allometric equations. Tree allometry generates a quantitative correlation between tree characteristics that are generally easy to measure (e.g. stem diameter and tree height) and other dendrometric characteristics that are difficult to measure (e.g. tree biomass). The obtained relationship allows extrapolation and estimation in other studies of interest (FAO and CIRAD Online 2014). However, specific allometric equations for the dominant or popular urban tree species are rare. This is because most accessible allometric equations were generally established for major tree species in traditional forest ecosystems where most urban tree species are uncommon (McHale *et al*., 2009).

The study site, Soweto is one of the most highly populated urban areas faced with massive backlogs of housing development and urban infrastructure in South Africa. The people of this township are renowned for their significant role in the struggle against the apartheid regime between 1940's-1990's. Under the apartheid government, residence and land ownership were racially segregated (Wilkson, 1998). A number of land areas were geographically zoned and the majority of black South Africans were constrained to reside in homelands or in high density townships, poorly serviced with little or no green spaces in what was referred to as the 'green divide'. The end of the apartheid regime after 1994 brought the need to address some of these challenges with more attention given to tree planting and distribution of public green spaces (Shackleton *et al.,* 2013). This was motivated by the perceived notion that the quality of life and urban sustainability involves urban resident access to urban trees and public green spaces (i.e. parks) (Sundaram, 2011).

The vision of the 'Greening Soweto' initiative by Johannesburg City Parks was to transform the dry, dusty streets and landfill sites that characterised Soweto and many black South African townships during the apartheid regime to award winning parks with a variety of ecological services (Johannesburg City Parks Online 2012). The project involved planting trees aimed at beautifying and creating a sustainable and habitable urban settlement, while at the same time ameliorating the effect of greenhouse gases and climate change (Barbosa *et al*., 2007; Nowak and Crane, 2002). It was underpinned by the South Africa's Mitigation Potential Analysis which identified urban tree planting as one of the important measure to contribute to GHG reduction (Department of Environmental Affairs Online 2015; DEA and GIZ 2014). Implementation of the project gained momentum during the period leading to the hosting of the 2010 soccer FIFA World Cup and the allocation of 'Beautification Funds' under the 'Greening Johannesburg Banner' (Johannesburg City Parks Online 2012). Thus, the world soccer event provided an opportunity to establish civic ownership and community pride. The project was commissioned in September 2006 with the initial target of planting between 20,000 and 200,000 urban trees in Johannesburg. By 2008, it had cost Johannesburg City Parks R46 million to plant over 51,821 in the parks and along the streets of Soweto (Johannesburg City Parks Online 2012). Driven by the success story of the 'Greening Soweto' project and other urban greening projects and the need to reduce the country's carbon footprint, additional multi–stage projects across the country have been launched to create green spaces in streets, homesteads, parks, public areas and rehabilitation sites (Department of Environmental Affairs Online 2015).

It is over eight years since the trees were planted and trees change in morphological appearance, height, girth and crown cover and increase in biomass and the amount of carbon stored, on an annual basis (Archibald and Bold, 2003). Thus, Johannesburg City Parks, an implementing organisation on behalf of the City of Johannesburg responsible for park development, conservation, management, beautification and urban greening, was interested in knowing to what extent carbon had been sequestrated by the trees in Petrus Molefe Park and Thokoza Park in Soweto. This would allow extrapolation of the methodology and procedure used in this study to a larger area where urban trees had been planted.

1.1. Aim of the study

The aim of this study was to use allometric equations to calculate above-ground tree biomass, carbon stored and the associated net economic value of the 'Greening Soweto' urban tree project in two selected sites.

1.2. Research questions

1. What is the amount of above-ground carbon stored?
2. What is the estimated Rand value of the carbon stored?
3. What is the net economic value of carbon stored?

1.3. Scope of the study

The study was restricted to tree species in Petrus Molefe Park and Thokoza Park in Soweto. Petrus Molefe Park consisted of recently planted tree species of approximately seven years old with two individual trees estimated to be over 30 years old, while Thokoza Park had older tree species estimated to be 25 years old, with some trees estimated to be over 30 years. Based on tree age and the attention given to curtail the spread of non-indigenous species, the two sites were used as contrasting sites to test the use of allometric approach in monitoring and evaluating urban forests, and to emphasise the use of indigenous species for carbon sequestration.

CHAPTER TWO

2. Literature review

2.1 Global warming and climate change

Global climate change refers to changes in the global long term weather patterns (i.e. temperature, precipitation, and rise in sea level). This is primarily caused by the increase in the global average temperature due to emission of greenhouse gases (i.e. water vapor, CO_2, nitrous oxide, methane and chlorofluorocarbon) into the atmosphere (IPCC 2007). However, it is almost impossible to maintain Earth's surface temperature without greenhouse gases as the planet would be cold, making it an uninhabitable planet for most life forms (Kump, 2011; Rockström, 2009; Shaffer and Carpenter, 2003). Energy from the sun reaches the Earth's surface as it passes through the atmosphere at a short wavelength. The Earth's surface absorbs some of the energy from the sun and radiates heat energy at a longer wavelength back to the atmosphere. Greenhouse gases trap the thermal/infrared radiation (longer wavelength) to keep the Earth surface warm in a phenomenon known as the greenhouse effect (Houghton, 2013). The higher the amount of greenhouse gases in the atmosphere, the more thermal radiation is trapped and the warmer the Earth (Bowler *et al*., 2010; IPCC 2007).

Carbon dioxide represents the main atmospheric phase of the Earth's biogeochemical cycle. Thus, the atmospheric concentration of CO_2 has been monitored in the last 400 years. The records indicate that since the Industrial Revolution (1700's) atmospheric CO_2 concentration has been increasing markedly. The concentration of CO_2 in the atmosphere has risen from approximately 280±10 parts per million (ppm) to the 2015 record high of 400 ppm and these trends are projected to continue into the future with a subsequent rise in global average temperature (United Nations Environment Programme 2015; IPCC 2007; IPCC 2001). Even though about half of anthropogenic CO_2 is absorbed through natural processes (Jones *et al*., 2006), studies suggest that feedbacks (climate-carbon feedbacks) will further reduce the ability of the terrestrial and oceanic carbon cycles to absorb anthropogenic CO_2. As a result, the carbon storage capacity of forest ecosystems and its potential to ameliorate climate change has become one of the focus areas of significant research (Stoffberg *et al*., 2010; IPCC 2007; McGranahan *et al*., 2005).

2.2 The global carbon cycle

The global carbon cycle comprises a number of carbon pools (such as CO_2 held in the atmosphere, dissolved CO_2 in the oceans and the terrestrial system) and fluxes such as photosynthesis and respiration. Even though the total carbon stocks is approximately 560 for plant biomass and 110 for microbial biomass (Lal, 2007; Houghton, 2007), the terrestrial carbon cycle, particularly tree biomass, is the most sensitive and variable pool. This is because the terrestrial carbon cycle is susceptible to anthropogenic perturbation (Houghton, 2007). During the process of photosynthesis, atmospheric CO_2 is converted to a range of metabolites which play a critical function in primary plant production (Pretzsch, 2009). The dynamics of the terrestrial carbon sinks involves an understanding of the global carbon budget.

According to Jansson *et al*., (2010), about 560 gigatons of carbon is stored in above-ground plant biomass, 110 gigatons in below-ground plant biomass and 2,500 stored in the soil. Annually, about 123 gigatons of carbon which is known as the Gross Primary Productivity (GPP) is captured through photosynthesis (Jansson *et al*., 2010). Forests have a unique ability to sequestrate carbon, because only 60 gigatons of the GPP is returned to the atmosphere through autorespiration while about 63 gigatons of carbon or the difference between GPP and autorespiration which is known as the Net Primary Production (NPP) is fixed by trees (Figure 1) (Houghton, 2007; Lal, 2007; Rogers *et al*., 1996). The Net Primary Productivity is used for growth (increase in biomass) and maintenance. However, through heterotrophic and microbial respiration, some carbon is lost to the atmosphere. The remaining carbon after heterotrophic and microbial respiration is referred to as the Net Ecosystem Productivity (NEP) which is approximately 10 gigatons of carbon (Jansson *et al*., 2010). The NEP is what regulates photosynthetic fixation of atmospheric CO_2. The Net Ecosystem Productivity (NEP) is determined by measuring the fluxes of CO_2 between the atmosphere and the terrestrial system and studies suggest that the value of NEP is variable between different forests, due to the differences in geographical locations, environmental conditions (e.g. temperature, rainfall), tree density, species and tree age (CIFOR Online 2015; Kipkorir araap Sigi Lang'al, 2013; Nowak and Crane, 2002; Bolin *et al*., 2000). Taking into account anthropogenic disturbance (i.e. fire, deforestation and degradation), the long term carbon stocks is often a percentage of NEP which is known as the Net Biome Productivity (NBP) (Jansson *et al*., 2010).

Similar to the above-ground stored carbon, the below-ground biomass and the associated soil carbon pool in the terrestrial system is an important carbon pool. Approximately 950 gigatons of soil inorganic carbon and 1550 gigatons of soil organic carbon is stored below-ground (Figure 1). One major difference from the above-ground stored carbon is that the soil carbon pool has a slower turnover due to the minimal effects of fire, deforestation and degradation (Lal, 2007).

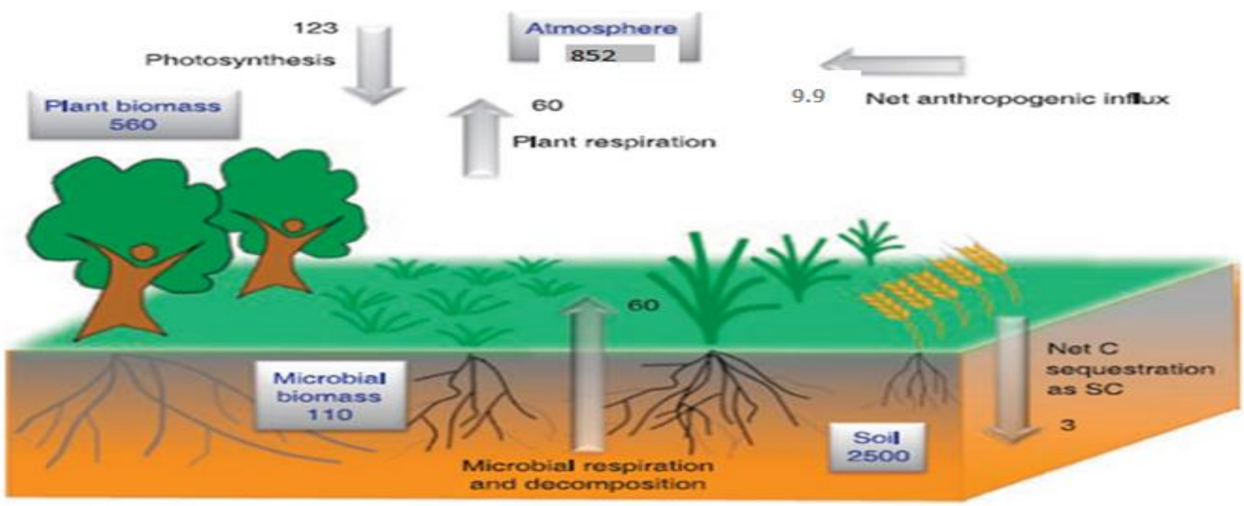

Figure 1: The global terrestrial carbon cycle (Source Lal, 2008; Houghton 2008; atmospheric carbon concentration was calculated based on the data from Willard Online 2013).

The boxes represent the total carbon stocks in gigatons, while the arrows are fluxes of carbon in gigatons per year. This natural cycle is pertubated by the emission of about 9.9 gigatons of carbon per year from anthropogenic activities. In the absence of fire, deforestation and degradation, the above-ground plant biomass stores about 560 gigatons of carbon and, below-ground plant biomass stores about 110 gigatons and the soil stores about 2,500 gigatons (Lal, 2007; Houghton, 2007; Jansson *et al*., 2010).

As stipulated by the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, South Africa is committed to contributing to climate change mitigation initiatives. Through the National Climate Change Response Policy (NCCRP), the country has developed a strategic approach for an effective climate change response and a long term transition to a climate-resilient, equitable and internationally competitive lower-carbon economy and society (DEA and GIZ 2014). This vision is premised on the country's commitment to sustainable development and a better living environment for all. The NCCRP outlines a strategic response to climate change within the context of South Africa's broader national development goals, which include economic growth, international economic competitiveness, sustainable development and improving public and environmental health, and poverty alleviation through job creation.

Under the NCCRP, the National Strategy for Sustainable Development (NSSD) has been identified and adopted. The strategy regards sustainability as a long term-commitment which integrates environmental protection, social equity and economic efficiency. Part of the NSSD are the two themes namely, green economy in the context of sustainable development and poverty eradication, and the institutional framework for sustainable development (Department of Environment Affairs Online 2015). Green economy is defined as "a system of economic developments related to the production, distribution and consumption of goods and services that result in improved human well-being over a long period without exposing future generations to significant environmental risks and ecological scarcities" (Department of Environmental Affairs, 2015; United Nation Environment Programme Online 2015). To achieve successful transition to the green economy, resource conservation and management is one of the nine key focus areas that have been recognised in the action plan. Under the resource conservation and management area, the national payments for ecosystem services, infrastructure resilience and ecosystems, and offset programme are included.

2.2.1 Urban tree planting in mitigating climate change

Urban greening also referred to as urban forests is defined as "the planting and management of individual trees and groups of trees in public and private open spaces in cities which are directly or indirectly available to the public" (Barbosa *et al*., 2007; Tuzin *et al*., 2002). Unlike non-urban forests which are harvested for commercial purposes (e.g. timber), urban forests particularly growing in protected areas such as parks and public open spaces could arguably have a long term greater impact per area (e.g. provision of ecosystem services). This is especially important as more than half of the world's population lives in urban areas (United Nations Department of Economic and Social Affairs 2014; McGranahan *et al*., 2005). Thus, urban forests have become an important part of the global terrestrial carbon cycle and for the green economy to mitigate climate change, while enhancing human well-being (United Nation Environment Programme 2015). The practice of urban greening can be extended to a number of habitats such as parks, streets and derelict corners where some trees generated naturally and are allowed to grow, while the majority are planted. Therefore, tree attributes, management requirements and the species (indigenous or non-indigenous species) to plant are important factors that can be considered during the urban tree planting planning phase. According to Norman and McDonald (2003), decisions on tree planting (e.g. type of species to plant) should be guided by the concept of sustainable development. For instance, deciding on planting non-indigenous trees should be based on ecological, social and economic principles being aware that non-indigenous species often become invasive by out competing indigenous species for space and resources (van Wilgen *et al*., 2012; CSIR 2011; van Wilgen and Moran, 2007).

Despite being a small percentage of the global terrestrial biomass because of low tree density and limited spaces in urban areas, recent studies indicate that urban greening has the potential to aid the global carbon cycle through carbon sequestration. This is consistent with the study by Nowak and Crane (2002) on carbon sequestration of urban trees in USA. The urban trees from 10 USA cities stored over 700 million tonnes of carbon, with an annual sequestration rate of over 22.8 million tonnes. Further, amounts ranging between 13.55-250 tonnes of carbon per hectare have been reported from urban forests from China, Indonesia and Kenya (CIFOR Online 2015; Kipkorir Sigi Lang'at, 2013). To ensure the country remain internationally competitive lower-carbon economy, in 1996 the South African National Department for Water Affairs and Forestry (DWAF) established an objective of promoting the sustainable management of forestry (1996) which was translated in 1997 into the National Forestry Action Plan and subsequently the Forest Act of 1998. The prime objective of the Forest Act was to promote sustainable development in the use of forests and by extension improving the living conditions of all South African people through projects such as school nurseries, urban and peri-urban tree plantings, individual fruit and shade tree plantings and transporting surplus wood to needy areas. Since then, preserving and enhancing natural capital (e.g. urban greening) has become an important strategic approach for climate change mitigation and adaptation (Nicholls and Vermaak, 2015).

2.2.2 South Africa's mitigation potential analysis: Urban tree planting

Mitigation Potential Analysis (MPA) is the measure of the quantified amount of greenhouse gas that can be reduced and measured against a baseline or any datum (DEA and GIZ, 2014). Mitigation potential measures that have been assessed and agreed to provide GHG mitigation abatement in South Africa are treatment of livestock waste, expanding plantations, urban tree planting, rural tree planting (thickets), restoration of mesic grasslands and addition of biochar to croplands (Figure 2).

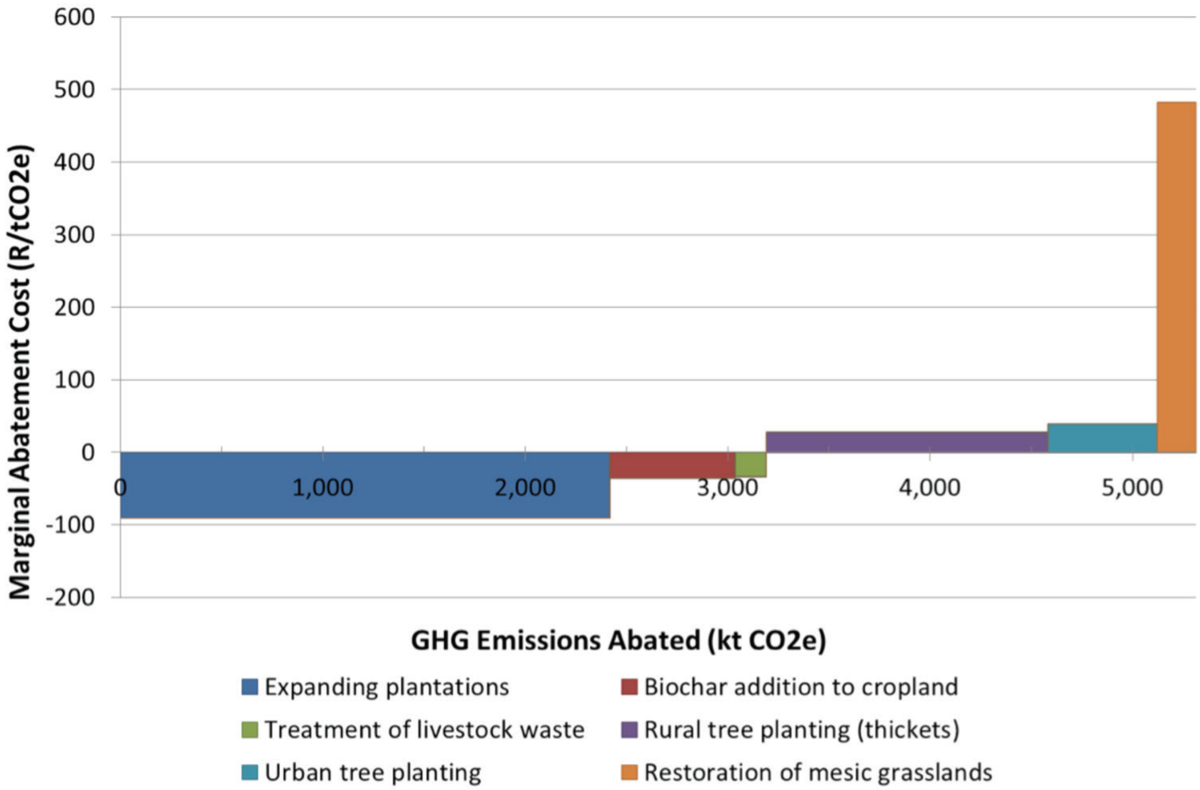

Figure 2: Marginal abatement cost curve for the six national mitigation potential measures. A marginal abatement cost curve shows the costs and potential for emissions reduction from different measures, ranking these from the cheapest to the most expensive to represent the costs of achieving incremental levels of emissions reduction. The estimation for 2020 indicate that urban tree planting projects will cost about R30/tCO_2e with the potential of mitigating about 700 ktCO_2e whereas the expanding plantations measure is not only cost effective (cost savings estimated to be R91/tCO2e), but it also mitigates the most emissions (an estimated 2,400 ktCO_2e). Where tCO_2e is tonnes of carbon dioxide equivalent, ktCO_2e is kilotonnes of carbon dioxide equivalent (Source DEA and GIZ 2014).

Tree planting measure (urban and rural) is concurrent with the proposed (first phase scheduled from 2016-2020) carbon price of R120 per tonne of CO_2 equivalent (R120 per tonne of CO_2e) for emission of CO_2 above the tax free thresholds (Department of National Treasury 2013). A basic tax free threshold is the 60% on actual emissions, below which organisations will not be liable to pay tax (Department of National Treasury 2013). Although the cost effectiveness of achieving emission reduction by urban tree planting ranks number five (estimated cost of R30/tCO_2e) in the MPA, it is envisaged that with carbon pricing and carbon offset systems urban tree planting will make a fair contribution to the national and international efforts to stabilise GHG concentrations in the atmosphere (Department of National Treasury 2013).

The proposed carbon price takes cognisance of the need for a smooth transition to a low carbon economy or an economy that produces minimal GHG emissions. Thus, national mitigation potential measures particularly tree planting projects (urban and rural) will provide additional alternatives and flexibility to minimise GHG emissions and to supply marketable carbon emission offsets (Department of Environmental Affairs, 2015; Department of National Treasury 2013) For instance, the Department of Environmental Affairs recently (in 2013) allocated R33 million to the Wildlands Conservation Trust to implement greening projects through the planting of 2,700,000 indigenous trees in Kwazulu-Natal and Mpumalanga and across five other District Municipalities namely, eHlanzini, Mgungundlovu, uMkhanyakude, uThukela and uThungulu with the aim of providing carbon credits (Department of Environment Affairs Online 2015). Through the trust, it was estimated that carbon will be traded at R100 per tonne to provide a source of income to the communities. With the estimated future increases (e.g. proposed 10% increase in carbon price in the second phase, 2021-2025) in market prices of offset credits and passage of mandatory regulations, carbon offsets in the South African proposed carbon pricing gives an opportunity to organisations, urban manager and municipalities planting and managing urban trees to generate revenue, while contributing to climate change mitigation initiatives (Department of National Treasury 2013).

2.3 Ecosystem services of urban trees

Human societies benefit from urban trees in a number of ways. The components and processes of forests which are directly enjoyed, consumed, or used to enhance human well-being are collectively known as ecosystem services (Millennium Ecosystem Assessment 2005; Robinson, 1996; United Nations Council for Environment and Development 1993). The ecosystem services provided by urban trees are environmentally, socially and economically valuable in a way that may not be easily perceived or understood. These services are classified in four broad categories namely supporting, provisioning, regulating, and cultural services (Figure 3) (Shackleton, 2013; Sundaram, 2011; Pataki *et al*., 2011).

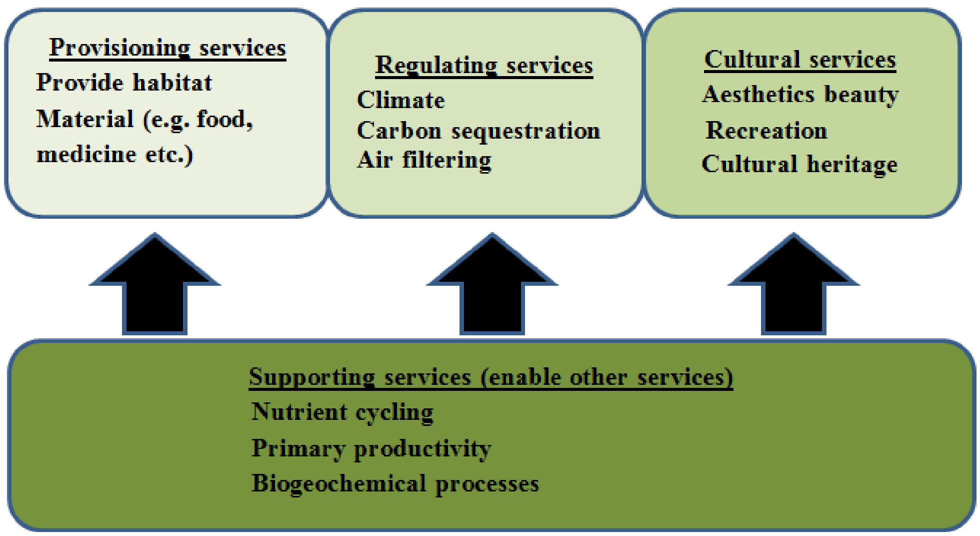

Figure 3: The four categories of ecosystem services (Source Millennium Ecosystem Assessment 2005).

- Supporting services are services that support and enable other ecosystem services (provisioning, regulating and cultural services). These services include biogeochemical processes such as: the water cycle, soil formation, the carbon cycle, primary productivity (photosynthesis) and nutrient cycling that allow transfer of energy between plants and animals.

- All the physical benefits obtained from urban trees are known as provisioning services. These include medicines, food, habitat, biodiversity etc.

- Regulating services are benefits derived from supporting a healthy ecosystem such as better air quality resulting from filtering air, climate regulation (e.g. carbon sequestration), prevention of soil erosion and pollination.

- All non-material benefits provided by urban trees are classified as cultural services. These include cultural heritage and identity, sources of education or learning and research, recreation and aesthetic beauty.

Quantifying and pricing of all goods, and services (ecosystem services) that promote the three pillars of sustainable development is a prerequisite for a green economy (World Business Council for Sustainable Development 2013). The three pillars of sustainable development are environmental, social and economic systems and benefits.

2.3.1 Environmental benefits

Urban forests can play a major role in improving urban environmental conditions in cities such as air quality, thermal conditions, reduce storm water runoff and carbon sequestration. The role of urban trees and urban forest in removing air pollutants (e.g. aerosols and dust) in urban areas has become of interest, especially in advancing habitability of urban areas. Recent large scale studies suggest that urban trees can improve air quality by 25% through filtering of small air particles (Stewart *et al*., 2001). Further, thermal imagery have been used to assess thermal conditions and to develop climate strategies for urban areas. The images indicate that trees and urban woodland (e.g. parks) covering more than one hectare of land are consistently among the coolest surfaces during hot summer days with temperature ranging 2-3°C lower than non-forested areas (Stewart *et al*., 2001). Conversely, during rainfall events when there is an increase in the flow intensity of surface water runoff which often cause strain of sewerage systems and dampen flows of catchments, a study by Xiao *et al*., (2000) reported that, "urban individual trees reduce surface water runoff by intercepting precipitation, storing and/or evaporating it and facilitating rain water infiltration into the soil".

The assumption that above-ground tree biomass consists of 50% carbon is commonly used in large scale forest carbon estimates in natural forests, temperate forests, urban forests and agroforestry systems (Thomas and Malczewski, 2007). Hence recent research interest has focused on the potential of urban trees and urban forests to mitigate climate change through carbon sequestration. However, using 50% as a conversion factor often results in either under-estimates or over-estimates of above-ground stored carbon of an individual tree and by extension forests. The Intergovernmental Panel on Climate Change (2006) offers an accurate and precise approach for estimating biomass carbon content of trees growing under the same and different conditions. The approach is based on chemical analysis of dry woody biomass. Henceforth, different studies have found variation ranging from 45-55% in wood carbon content across forests, and between angiosperms and conifers (Elias and Potvin, 2003; Lamlom and Savidge, 2003). These studies underscore the environmental benefits of trees and forests in providing regulating services (e.g. carbon sequestration).

2.3.2 Economic benefits

Estimating the monetary or economic value of urban forest ecosystem services is important in managing the interaction between humans and ecosystems (Spash, 2012; Howarth and Farber, 2002). Although this is a difficult undertaking due to the numerous benefits obtained from urban trees, marginal benefits (e.g. economic value of carbon stored) can be used to provide information on the structure and functioning of an ecosystem and basis for a national 'Payment for Ecosystems Services' scheme (UNFCCC 2011; UNREDD 2010; World Bank 2005; Howarth and Farber, 2002). In addition to the potential of urban forests to provide carbon credits for the benefit of the communities, the United Nations Reducing Erosion from Deforestation and Forest Degradation (UNREDD) and the World Bank offer payments for tree protection and increasing tree cover to developing countries. The UNREDD schemes are aimed at providing a financial incentive to goverments, agribusinesses and communities to establish and maintain forests and in the long term, while alleviating urban and rural poverty (UNREDD, 2010; Barbosa *et al*., 2007). For instance, based on forest monitoring and evaluation done by some members of the community, a combined total of $515 million was paid to the agencies of the three urban tree projects (National Government in Benin, Green Resources Busoga in Tanzania and New Forests Company in Uganda) in Africa (Jindal *et al*., 2008).

2.3.3 Social benefits

Urban green spaces such as trees planted along the streets and parks do not only provide aesthetic benefits to the landscapes, they also have an impact on critical social benefits such as health care, education, and providing areas for recreation and entertainment, and empowerment at individual, organisation or community level (Westpal, 2003). Another important health and social benefit to urban residents is the shade provided by urban trees. A study by the National Urban Forestry Unit (NUFU) (1999; 2002) observed that an individual tree can provide a Sun Protection Factor of up to 10 thus, reducing the level of exposure to ultraviolet radiation (NUFU, 1999).

The other identifiable social benefit of urban tree planting projects is the creation of 'Green jobs'. The United Nations Environmental Programme define Green jobs as "work provided by the agriculture, research and development, administrative and service activities that contribute substantially to preserving or restoring environmental quality and protecting ecosystems and biodiversity." Because tree planting projects is labour intensive, they often provide jobs particularly to members of the communities before, during and after the project (Westpal, 2003). This is important from the social perspective (e.g. anti-social behaviour) because such opportunities ensure that at least some members feel ownership of the project. Further, Stringer *et al*., (2006) identified multi-stakeholder participatory in urban greening initiatives as another form of community empowerment and the primary mechanism through which long term social learning and benefits can be realised (Stringer *et al*., 2006).

The ecosystems services offered by urban green spaces demonstrate the multifunctional uses and benefits of urban green spaces that add to habitability of urban areas. This emphasise the need to protect and conserve ecosystems and biodiversity (e.g. tree species) (Department of Environmental Affairs, 2015). In this context, the Green Economy Initiative led by the United Nation Environment Programme sets out a framework that provide support for monitoring and evaluating (such as use of allometric equations) forest inventories while ensuring environmental protection. This is because estimating tree biomass using destructive sampling is expensive, labour intensive and does not protect individual tree species and forests (CIRAD and FAO 2014).

2.4 Estimating tree biomass using destructive sampling

Even though there are a number of available methods (e.g. remote sensing and models based on statistical inventories of trees) for estimating forest biomass, destructive methods involving cutting and weighing tree components remains the most commonly used approach. This is because many other methods (e.g. allometric equations and statistical model based methods) are constructed from the destructive method (FAO and CIRAD 2012). The procedure involves five main steps namely, tree felling, measuring tree characteristics, cross-cutting and weighing samples in the field, oven drying samples in the laboratory, and weighing and calculation of tree biomass (FAO and CIRAD 2012).

- Step1: Prior to felling the tree of interest, the breast height (1.3 m) of the tree stem is identified and marked. This is important when developing allometric equations as the tree is never cut at ground level. Further, small stems that could hinder tree fall are cut and the area cleared. The area is covered with a tarpaulin for easy collection of samples.

- Step 2: Stem circumferences is measured at 1.3 m and every one metre of the trunk from diameter at breast height to the tip of the tree. This is useful for constructing stem profile models. Tree height is also measured on the main stem. If the stem is extensively twisted, a principal axis is identified and marked and measured as the true height.

- Step 3: During cross-cutting and weighing, the branches and leaves are first separated from the stem. Branches are cut and bundled into diameter classes while leaves are stripped off and put in large sacks. Secondly, the stem is cross-cut into disks and labelled to indicate its position on the trunk. Before being transported to the laboratory, all the samples are weighed in the field under the same relative humidity conditions.

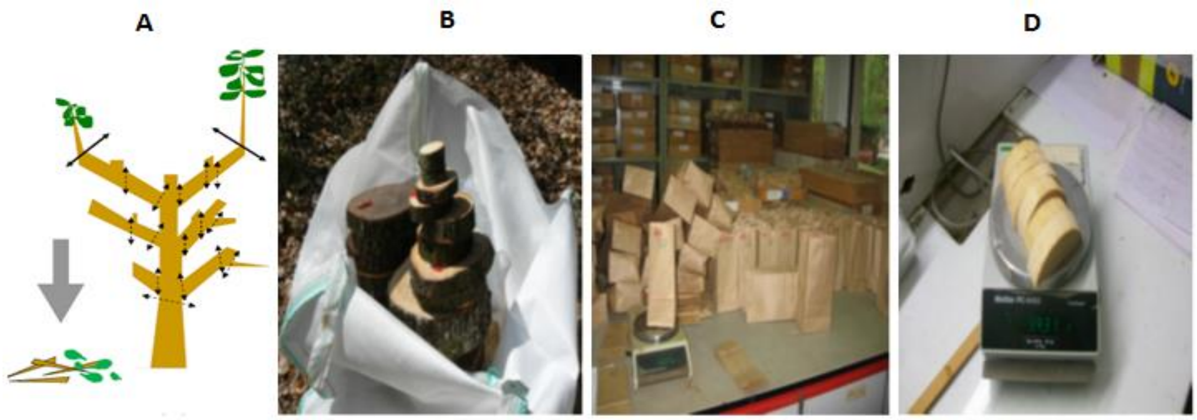

Figure 4: Procedure for estimating tree biomass using a destructive method (Source FAO and CIRAD 2012).

Figure 4(A-D) shows (A) tree felling, (B) cross-cutting stem and branches into disks, and collection of leaves, (C and D) drying and weighing of samples in the laboratory and (E) calculation of biomass (not shown).

- Step 4: Oven-drying of samples in the laboratory involves scheduled weighing of the samples until a constant weight is attained. A temperature of 70°C is recommended for leaves and 105°C for woody structures. A constant leaf weight is generally reached after two days, while woody disks take about one to two weeks depending on the size of the sample.

- Step 5: Weighing and calculating biomass. The oven dry weights of all the samples are summed to obtain the total tree biomass.

There is such a large amount of work associated with destructive sampling henceforth, allometric equations based predominately on variables of diameter at breast height or both diameter at breast height and tree height have been developed (Green *et al*., 2007; Chave *et al,* 2005; Wirth *et al*., 2004).

CHAPTER THREE

3. Methods

3.1. <u>Study site description</u>

The two study areas (Petrus Molefe Park and Thokoza Park) are located in Soweto, approximately 21 km south of Johannesburg, South Africa (26°16’13.3” S 27°52’52.7” E). Petrus Molefe Park is a long narrow area approximately 9.29 hectares in extent and lies along Chris Hani Road and Jacaranda Avenue/Mtambo Street in Dlamini (Figure 5 and 6). The park was characterised by recreation facilities, indigenous and non-indigenous trees. The trees were estimated to be about seven years old with two individual trees estimated to be greater than 30 years old.

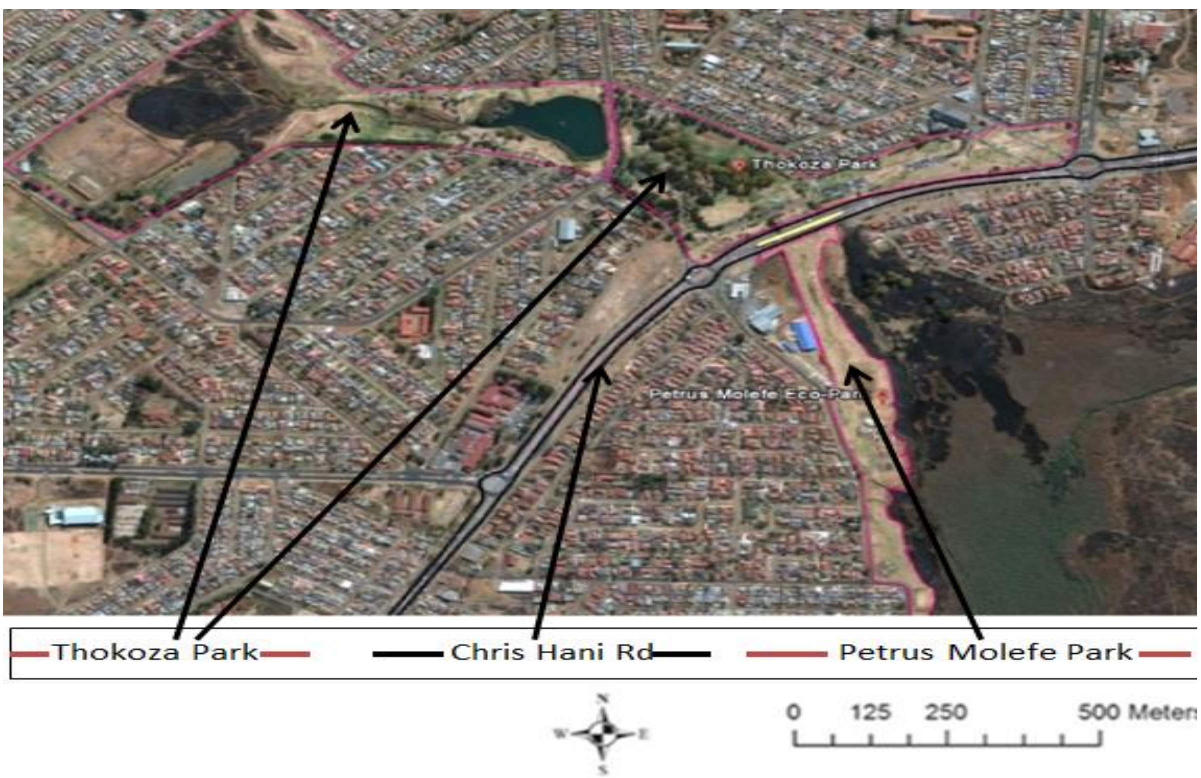

Figure 5: Aerial view of the two study sites, Petrus Molefe Park and Thokoza Park in Soweto, Johannesburg. The map shows that the two parks are spatially adjacent (Source: Johannesburg City Parks Online 2014).

Figure 6: Detailed aerial view showing the study site displayed within the white boundary, Petrus Molefe Park in Dlamini in Soweto, Johannesburg (Source: Google Earth).

Figure 7: Detailed aerial view showing the study site displayed within the white boundary, Thokoza Park in Rockville in Soweto, Johannesburg (Source: Google Earth).

Thokoza Park is adjacent to Petrus Molefe Park extending to Vundla Street and Ntuli Street near the renowned Regina Mundi Church. The area sampled covered approximately 3.33 hectares of the total 4.5 hectares of Thokoza Park (Figure 7). It was characterised by recreation facilities, a stream running across the park, leading to Moroka Dam, and indigenous and non-indigenous trees estimated to be about 25 years old and some trees estimated to be over 30 years old.

Multi-year climate data (for the period 1985 to 2014) show that the mean annual rainfall ranges from 548±74 to 819±55 mm. The monthly average rainfall ranges from 4 to 151 mm, with the highest rainfall recorded in December and minimum in the driest month of July (Figure 8). The average temperature is 9.5±4 to 23±3^{0}C (Figure 9).

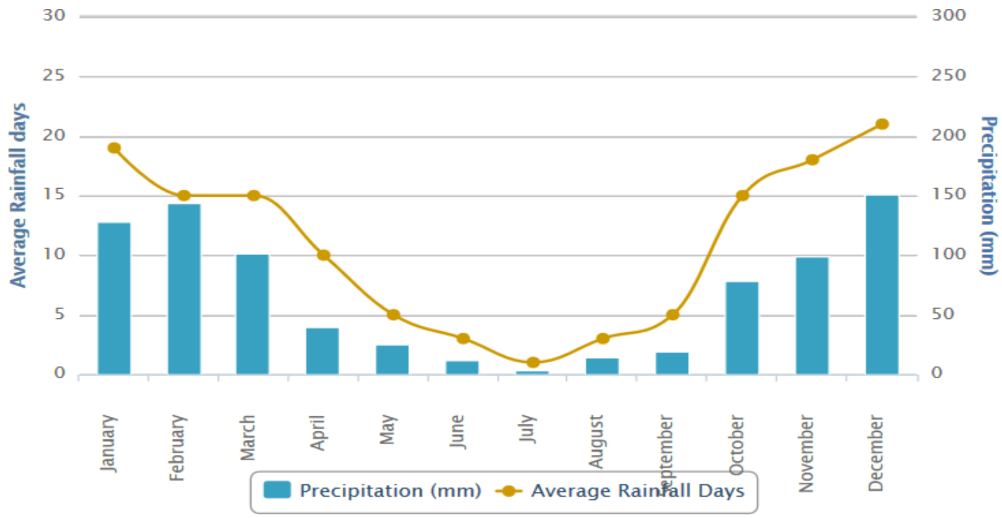

Figure 8: Monthly average precipitation (mm) and average rainfall days for Soweto, Johannesburg, South Africa (Source Worldweather Online 2015).

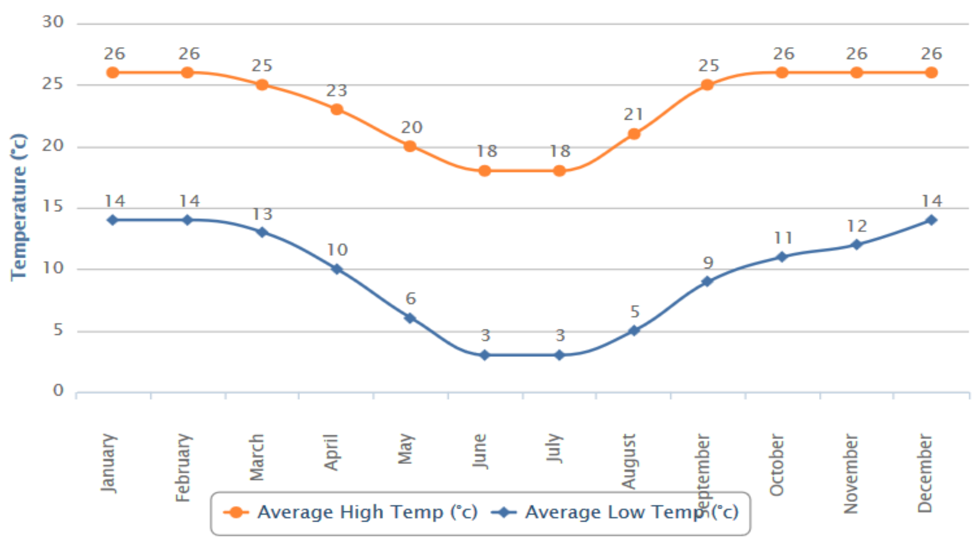

Figure 9: Average high temperature and average low temperature (°C) for Soweto, Johannesburg, South Africa (Source Worldweather Online 2015).

3.2. Experimental design and materials

During the winter (June-August) of 2014, 414 individual trees were identified and measured for specific characteristics (diameter at breast height and tree height) in Petrus Molefe Park. In contrast, 294 individual trees were identified and also measured for diameter and tree height in Thokoza Park. Identification of the collected specimens was done using various resources including 'Plant field trip guide books' and expert identification available in the Life Sciences Museum (Herbarium), School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, Johannesburg.

Circumference at breast height (1.3 m) was measured with a measuring tape marked in cm (Figure 10a). Circumference at breast height was preferred to diameter at breast height because it is a more accurate measurement for irregularly shaped stems. Tree height was measured using a ranging-rod for trees less than 5 m (Figure 10b) and a clinometer for taller trees. If the tree had been pushed over by storms, animals or people and growing at an angle, the slanting length was measured as the true vertical height.

Figure 10a: Measuring tree circumference at breast height (cm)

Figure 10b: Measuring tree height (m)

Figure 10a and 10b showing the equipment and method used in measuring circumference at breast height and tree height (Source: Photos taken from Petrus Molefe Park, 2014).

Circumference was converted to diameter and radius using equations 1 and 2.

$$DBH = CBH/\pi \quad (1)$$

$$r = DBH/2 \quad (2)$$

Where DBH is diameter at breast height (cm), CBH is circumference at breast height (cm), π=3.142 and r is the stem radius.

3.2.1. Allometric equations: Calculation of above-ground biomass

According to Gould (1966) characteristics measurements (e.g. diameter, tree height, crown height and biomass) of an individual tree are statistically related. This biological rule originates from the ontogenic development of individual trees (small or big) which is similar for all species as long as they are growing under similar conditions (FAO and CIRAD 2012). An example of such a biological rule is that the tree cross-sectional area below a fork is statistically the same as the combined cross-sectional area of the branches above-the fork otherwise, it would not be able to fit in the same number of tracheids transporting water from the roots to the crown. Therefore, regardless of size and species, the proportions between diameter and height, between diameter and crown height, between diameter and biomass follow this biological rule (Archibald and Bond, 2003). This basic principle of tree allometry is used to predict tree biomass from another variable (e.g. diameter)(Tumwebaze *et al*., 2013; Ciencilia, 2006). An allometric equation (e.g. of the form $Y=ax^n$) is a formula that quantitatively describes the relationship.

Constructing allometric equations from destructive methods involves firstly, transferring the measurements recorded in the field and laboratory (from destructive sampling) onto a computer programme (i.e. Microsoft Excel). Thereafter, data are organised in a format appropriate for calculations and model construction (FAO and CIRAD 20012). Secondly, measured variables are plotted using a scatter graph and through graphical exploration, the model best fitting the data is selected. The best fit is the model which minimises the residual error of the sum of squares. The sum of squares of residuals is the actual observations less the predictions, whereas the values *a* and *b* are coefficients that minimise the sum of squares. Further, the coefficient of determination (R^2) measuring the quality of the fit or the ratio (ranging 0-1) between the variance explained by the model and the total variance is analysed. Thirdly, the model is checked and validated for applicability. This is done by comparing it with observations independent of those used for fitting it (Rykiel, 1996). The criteria used to validate the quality of model fitting are: sum of squares of the residuals (SSE), fitted residual error, residual variance (s^2), bias and coefficient of determination of the regression (R^2) (Nickless *et al*., 2011).

Before deciding on the model to use, it is important for researchers to check the characteristics of the trees to be estimated. This is because some equations are constructed for specific tree species and diameter range and in principle cannot be used to estimate biomass of trees whose diameter is outside the valid range. These equations are known as specific allometric equations (Globallometree Online 2014). On the other hand, power model based equations (e.g. ax^n) validated on more than one species often yield reliable biomass estimations of different species and diameter ranges. This is because they are based on a fractal allometric model that is invariant on all scales (Zianis and Mencuccini, 2004). These allometric equations are referred to as general allometric equations (Chave *et al*., 2005; Tietema, 1993; Rutherford, 1979). Hence, the use of allometric equations has been widely adopted as an important tool for advancing sustainability.

In this study a general allometric equation was preferred as it accurately estimates above-ground biomass and avoids destruction of trees. Unlike specific allometric equations which are often restricted to one particular species, general allometric equations are extensive and are used to estimate numerous broad leaved species or narrow (scale-like) leaved species. Above-ground biomass (kg) was calculated using a general allometric equation by Tietema (1993).

$$Y=aX^b \qquad (3)$$

$$\text{or} \quad Y=a(\pi r^2)^b \qquad (4)$$

Where Y is above-ground biomass in kg, X is stem cross-sectional area in cm, r is stem radius in cm, a=0.1936 and b=1.1654 and π=3.142. The allometric equation only uses diameter at breast height and does not include tree height (Tietema 1993). The purpose of measuring tree height was to establish if there was a relationship between diameter at breast height and tree height.

3.2.2. Conversion of above-ground biomass to the amount of carbon stored

Above-ground biomass (kg) was converted to stored carbon values using 45% as the conversion factor. Usually, 45% is the average carbon content value for dry terrestrial biomass. This assumption was according to the recent studies which states that carbon concentration of woody tree components varies from 45 to 55% (Martin and Thomas 2011; Thomas and Malczewski, 2007).

3.2.3. Conversion of carbon stored to an economic value

The cost of planting trees in the two parks was R1,200 per individual tree. However, converting ecological services of urban trees to economic values is a new concept in developed and developing countries or emerging economies such as South Africa. Based on the proposed carbon price of R120 per tonne of carbon dioxide equivalent (R120/tonne of CO_2-e) (Department of National Treasury, South Africa 2013) and the carbon dioxide to carbon atomic ratio; 3.67 (equation 5), the carbon price of sequestrated carbon was calculated at an equivalent price of R440.40 per tonne of carbon (equation 6).

$$K = CO_2\,(44)/C\,(12) \quad (5)$$

$$P_3 = K \times P_2 \quad (6)$$

Where K is the atomic ratio of CO_2 (44) to C (12), P_3 is the carbon price of sequestrated carbon per tonne and P_2 is the proposed carbon price of (R120/tonne of CO_2-e). Therefore, the associated net economic value of carbon sequestrated was the carbon price less the cost of planting the trees (equation 7).

$$P_4 = P_3 - nP_1 \quad (7)$$

Where P_4 is the net economic value (Rand), P_3 is the carbon price per tonne, n is the number of individual trees and P_1 is the cost of planting trees of R1, 200 per individual tree.

3.3. Statistical analysis

Analysis of variance (ANOVA) using R was used to establish if there is any significant difference within the mean diameter and mean tree height of different species in each site, and above-ground tree biomass and carbon stored between Petrus Molefe Park and Thokoza Park. Further, analysis was conducted on the dominant tree species to establish if there is any relationship between diameter at breast height and above-ground biomass, and between diameter at breast height and tree height.

CHAPTER FOUR

4. Results

4.1. <u>Biomass, carbon stored and the associated net economic value</u>

The 414 individual trees (indigenous and non-indigenous) in Petrus Molefe Park had a total above-ground biomass of 7.45 tonnes, total carbon stocks of 3.35 tonnes at an estimated value of R1,475.34 and the associated net economic value of R-495,324.66 (Table 1). *Franxinus americana* was categorised into two groups. The first group had one individual tree which was approximately seven years old, while the second group had two individual trees estimated to be approximately over 30 years old. The two individual trees of *Franxinus americana* estimated to be approximately over 30 years old had the largest above-ground biomass; 3.47 tonnes and a carbon stock of 1.56 tonnes, which represented 47% of the total above-ground biomass and carbon stored in Petrus Molefe Park. Among the five dominant tree species, namely *Celtis africana*, *Celtis sinensis*, *Combretum erythrophyllum*, *Olea africana* and *Searsia lancea*, *Celtis sinensis* had the largest values with reference to the number of individual trees; 165, total above-ground biomass; 1.37 tonnes, the amount of carbon sequestrated; 0.62 tonnes and the associated net economic value; R273.05. The 84 individual trees of *Olea africana* had the lowest values of above-ground biomass; 0.44 tonnes, carbon stored; 0.20 tonnes, and the associated net economic value of R88.08.

In contrast, the 16 tree species (indigenous and non-indigenous) in Thokoza Park were categorised into two age groups. *Acacia karroo, Acacia sieberiana*, *Acer palmatum*, *Franxinus velutina*, *Populus nigra*, *Salix alba*, *Salix babylonica*, *Schinus molle* and *Sophora japonica* were estimated to be approximately over 30 years old. Whereas *Acacia galpinii*, *Celtis africana*, *Combretum erythrophyllum*, *Olea africana*, *Searsia lancea*, *Celtis sinensis* and *Ligustrum lucidum* were estimated to be about 25 years old. The 294 individual trees in the park had a total above-ground biomass of 205.76 tonnes, 92.59 tonnes of carbon stock at an estimated value of R40,776.64 and the associated net economic value of R-312,023.36 (Table 2). Trees estimated to be approximately over 30 years old had the largest values of above-ground biomass and carbon stocks. For instance, the total above-ground biomass and carbon stocks for Acacia *karroo*, *Populus nigra* and *Salix babylonica* represented 68% of the total above-ground biomass and carbon stored in the park. By comparison, trees estimated to be about 25 years old had the lowest above-ground biomass and carbon stored.

Table 1: Results of above-ground biomass, carbon stored and net economic value of tree species in Petrus Molefe Park (indigenous species are depicted in 'blue font', whereas species in 'black font' are non-indigenous trees)

Tree species	Estimated Average age (years)	Number of trees	Mean Diameter ± Standard Deviation (cm)	Total Diameter (cm)	Mean height ± Standard Deviation (m)	Total height (m)	Mean biomass ±Standard Deviation (kg)	Total above-ground biomass (tonnes)	Total carbon stored (tonnes)	Carbon price (Rand)	Net economic value (Rand)
Acacia galpinii	7	12	13.57±2.19	162.84	4.51±0.59	54.12	66.18±25.60	0.79	0.36	158.54	-14,241.46
Acacia karroo	7	1	4.742±0.000	4.742	1.500±0.000	1.500	5.499±0.000	0.005	0.002	0.88	-1,199.12
Celtis africana	7	48	5.22±2.89	250.56	3.56+1.24	170.88	10.08±10.67	0.48	0.22	96.89	-57,503.11
Combretum erythrophyllum	7	63	4.85±2.34	305.55	2.68±1.08	168.84	7.94±10.00	0.50	0.23	101.29	-75,498.71
Olea africana	7	84	4.32±1.52	362.88	3.43±0.69	288.12	5.27±4.38	0.44	0.20	88.08	-100,711.92
Podocarpus henkelii	7	1	6.111±0.000	6.111	5.000±0.000	5.000	9.930±0.000	0.010	0.005	2.20	-1,197.80
Searsia lancea	7	14	6.87±3.73	96.18	3.13±0.98	43.82	18.60±19.69	0.26	0.12	52.85	-16,800.00
Searsia pendulina	7	10	4.44±1.81	44.40	4.30±0.66	43.00	5.86±6.54	0.06	0.03	13.212	-11,986.79
Celtis sinensis	7	165	4.92±2.42	811.80	3.84±1.68	633.60	8.27±9.12	1.37	0.62	273.05	-197,726.95
Franxinus americana (1)	7	1	11.27±0.00	11.27	4.00±0.00	4.00	41.327±0.00	0.04	0.02	8.81	-1,191.19
Franxinus americana (2)	Over 30	2	55.86±4.28	111.72	17.00±0.00	34.00	1,732.81±307.85	3.47	1.56	687.02	-1,712.98
Platanus acerifolia	7	13	2.70±0.97	35.10	2.49±0.93	32.37	1.75±1.07	0.02	0.01	4.40	-15,595.60
Total		**414**						**7.45**	**3.35**	**1,475.34**	**-495,324.66**

Note: The net economic value was the total carbon price less the cost of planting the trees of R1,200 per tree, (total cost of planting the trees was the number of trees multiplied by R1,200).

Table 2: Results of above-ground biomass, carbon stored and net economic value of tree species in Thokoza Park (Indigenous species are shown in a 'blue font' while non-indigenous trees are in 'black font')

Tree species	Estimated average age (years)	Number of trees	Mean Diameter ± Standard Deviation (cm)	Total Diameter (cm)	Mean height ± Standard Deviation (m)	Total height (m)	Mean Above-ground biomass ±Standard Deviation (kg)	Total above-ground biomass (tonnes)	Total carbon stored (tonnes)	Carbon price (Rand)	Net economic value (Rand)
Acacia galpinii	25	10	31.60±7.53	316.00	8.93±0.30	89.30	493.35±248.84	4.93	2.22	977.69	-11,022.31
Acacia karroo	Over 30	32	37.16±18.76	1,189.12	12.90±4.38	412.80	924.54±960.47	29.59	13.32	5,866.13	-32,533.87
Celtis africana	25	11	21.34±5.50	234.74	7.03±1.41	77.33	218.88±106.02	2.41	1.08	475.63	-12,724.37
Combretum erythrophyllum	25	31	21.68±5.75	672.08	8.92±1.79	276.52	210.44±134.35	6.52	2.93	1,290.37	-35,909.63
Olea africana	25	13	12.61±10.36	163.93	6.00±2.71	78.00	105.56±123.59	1.37	0.62	273.05	-15,326.95
Searsia lancea	25	32	22.50±6.37	720.00	7.14±1.52	228.48	231.65±136.54	7.41	3.33	1,466.53	-36,933.47
Acacia sieberiana	Over 30	1	45.99±0.00	45.99	9.30±0.00	9.30	1,096.58±0.00	1.10	0.50	220.20	-979.80
Acer palmatum	Over 30	2	26.10±2.70	52.20	10.90±0.71	21.80	295.21±70.64	0.59	0.27	118.91	-2,281.09
Celtis sinensis	25	23	26.61±7.67	612.03	8.44±2.24	194.12	343.63±202.15	7.90	3.56	1,567.82	-26,032.18
Franxinus velutina	Over 30	4	37.00±8.22	148.00	11.35±0.44	45.40	699.02±381.44	2.80	1.26	554.90	-4,245.10
Ligustrum lucidum	25	75	6.37±3.09	477.75	3.30±0.67	247.50	14.92±14.47	1.12	0.50	220.20	-89,779.80
Populus nigra	Over 30	8	64.11±11.20	512.88	24.36±0.83	194.88	2,476.36±937.63	19.81	8.91	3,923.96	-5,676.04
Salix alba	Over 30	3	54.00±21.95	162.00	10.40±0.00	31.20	1,872.70±1,756.70	5.62	2.53	1,114.21	-2,485.79
Salix babylonica	Over 30	29	66.89±23.01	1,939.81	16.81±1.55	487.49	3,095.54±2,419.24	89.77	40.40	17,792.16	-17,007.84
Schinus molle	Over 30	16	49.02±14.00	784.32	10.76±2.46	172.16	1,423.84±932.71	22.78	10.25	4,514.10	-14,685.90
Sophora japonica	Over 30	4	32.07±8.24	128.28	11.55±2.08	46.20	510.16±308.20	2.04	0.92	405.17	-4,394.83
Total		**294**						**205.76**	**92.59**	**40,776.64**	**-312,023.36**

Note: The net economic value is the carbon price less the cost of planting trees of R1,200 per tree (number of trees multiplied by R1,200)

In the last 18 years, South Africa has adopted a number of national scale alien plant control strategies (van Wilgen *et al*., 2012). These strategies call for reducing the risk of new introductions and the control of existing species by identifying and quantifying the full range or distribution of non-indigenous plants (van Wilgen and Moran, 2007). This is because non-indigenous species often become invasive and unsustainable by out competing indigenous species for space and resource (CSIR 2011). To advance these strategies, species in Petrus Molefe Park and Thokoza Park were divided into indigenous species and non-indigenous species. Table 2 and 3 present the results for above-ground biomass, carbon sequestrated and the net economic value for Petrus Molefe Park and Thokoza Park, respectively. The total diameter and total height was the number of individual trees per species multiplied by the mean diameter at breast height and mean height. Using the general allometric equation of $Y= aX^b$, the mean biomass in kg was the total above-ground biomass (AGB) of individual trees per species divided by the number of trees. Whereas the amount of carbon stored per species was the total above-ground biomass (tonnes) per species multiplied by the conversion factor of 0.45. The carbon price was the amount of carbon stored multiplied by the equivalent carbon price of R440.40 per tonne of carbon. Therefore, the net economic value was the total carbon price per species less the total cost of planting trees of R1, 200 per individual tree. The total values of above-ground biomass, total carbon stored, total carbon price and the total net economic value were the summed values of the 11 and 16 species in Petrus Molefe Park and Thokoza Park, respectively.

The 412 individual trees estimated to be about seven years old comprised of eight indigenous species (398 individual trees) and three non-indigenous species (14 individual trees). Indigenous species with an average above-ground biomass of 9.85kg or 0.01 tonnes per tree contributed a total of 3.92 tonnes of AGB whereas the non-indigenous species with an average AGB of 4.29kg per tree contributed 0.06 tonnes to the total AGB (7.45 tonnes) in Petrus Molefe Park. With reference to *Acacia galpinii*, *Celtis africana*, *Combretum erythrophyllum, Olea africana*, *Searsia lancea*, *Searsia pendulina*, *Celtis sinensis* and *Platanus acerifolia* in Petrus Molefe Park (Table 2), results indicated that tree species with higher values of mean diameter at breast height had higher corresponding values of mean above-ground biomass, while tree species with low values of mean diameter at breast height had low corresponding values of above-ground biomass. For instance, the largest mean diameter of 13.57±2.19 cm for *Acacia galpinii*, 6.87±3.73 cm for *Searsia lancea* and 5.22±2.89 cm for *Celtis africana* corresponded to the largest values of above-ground biomass of 66.18±25.60, 18.60±19.69 and 10.08±10.67 kg, respectively. The lowest mean diameter of 2.70±0.97 for *Platanus acerifolia*, 4.32±1.52 for *Olea africana* and 4.44±1.81 cm for *Searsia pendulina* corresponded to the lowest mean above-ground biomass of 1.75±1.07 kg, 5.27±4.38, 5.86±6.54, respectively. Furthermore, the mean above-ground biomass of the tree species estimated to be about seven years old revealed that *Acacia galpinii* had the highest mean above-ground biomass of 66.18±25.60 kg, while *Platanus acerifolia* had the lowest mean above-ground biomass of 1.75±1.07 kg. Assuming that the relationship between tree age and above-ground biomass is linear (which is just an assumption for illustrative purposes), the results indicate that growth rate was highest; 9.45 kg/year for *Acacia galpinii* and lowest; 0.25 kg/year for *Platanus acerifolia*. This implies that *Acacia galpinii* was the most effective tree species in the park with regard to carbon sequestration.

On the other hand, the tree species estimated to be over 30 years old in Thokoza Park had the largest mean above-ground biomass ranging from 295.21±70.64 to 3,095.54±2,419.24 kg and lowest mean above-ground biomass for the tree species estimated to be about 25 years ranging from 14.92±14.47 to 493.35±248.84 kg. Similarly, assuming the relationship between tree age and above-ground biomass was linear, the growth rate was 19.73 kg/year for *Acacia galpinii* and 0.75 kg/year for *Ligustrum lucidum*. The 294 individual trees in the park consisted of indigenous and non-indigenous species. However, the six indigenous species (129 individual trees) with an average above-ground biomass (AGB) of 0.40 tonnes per tree, contributed less total AGB of 52.23 tonnes than the 10 non-indigenous species (162 individual trees) with an average AGB of 0.95 tonnes per tree contributed 153.53 tonnes to the total above-ground biomass of 205.76 tonnes in Thokoza Park.

A contrast between the two sites showed that the 294 older trees covering 3.33 hectares of Thokoza Park sequestrated an average of 27.8 tonnes of carbon per hectare greater than an average of 0.36 tonnes of carbon per hectare sequestrated by the 414 younger trees covering 9.29 hectares of Petrus Molefe Park. Statistically, there was a significant difference (F value; 5.98 > F critical; 4.30) between the mean above-ground biomass and mean carbon stored between the two parks. It was found that AGB and carbon stored in Thokoza Park was greater than AGB and carbon stored in Petrus Molefe Park, being aware that the two sites had different species of different ages. Thus suggesting that the ability of younger trees (Petrus Molefe Park) to sequestrate carbon will increase with age.

4.2. Descriptive statistics of diameter at breast height

The diameter values were very variable within trees of the same species and between trees of different species. The variance ranged from 0.35 to 17.60 cm for Petrus Molefe Park and 2.07 to 116.17 cm for Thokoza Park. Analysis of variance (ANOVA) indicated that there was a statistical significant difference between the mean diameter of tree species within each park (F value; 20.17 > F critical; 1.85 for trees in Petrus Molefe Park and F value; 57.07 > F critical; 1.73 for trees in Thokoza Park). Trees in Thokoza Park had a greater difference among the means than the trees in Petrus Molefe Park. This suggests that the growth rate or increase in stem diameter varied significantly in older trees (Thokoza Park) than in the younger trees (Petrus Molefe Park).

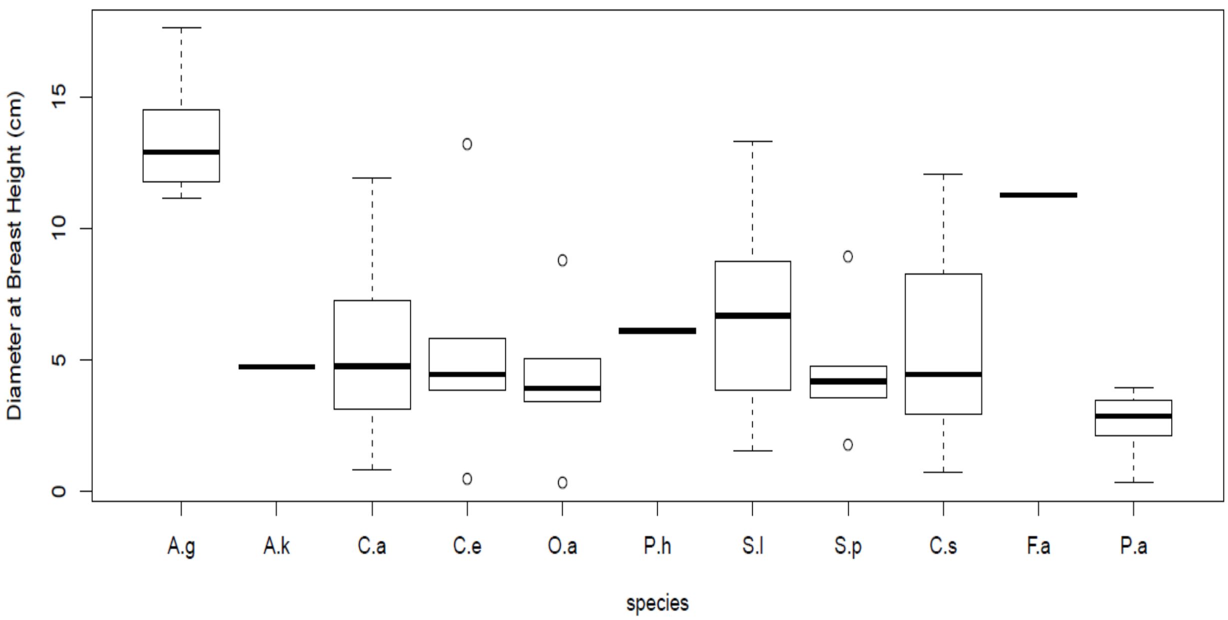

Figure 11: Distribution of diameter at breast height for the trees in Petrus Molefe Park.

Figure 11, showing the distribution of diameter at breast height for tree species in Petrus Molefe Park (*Franxinus americana* estimated to be 30 years old is not shown). Where, A.g; *Acacia galpinii*, A.k; *Acacia karroo*, C.a; *Celtis africana*, C.e; *Combretum erythrophyllum*, O.a; *Olea africana*, P.h; *Podocarpus henkelii*, S.l; *Searsia lancea*, S.p; *Searsia pendulina*, C.s; *Celtis sinensis*, F.a; *Franxinus americana* and P.a; *Platanus acerifolia*. The lowest whisker, lowest box margin, 'black-bold line', highest box margin and the highest whiskers represent the smallest diameter at breast height, the 25th percentile, median, 75th percentile and the largest diameter at breast height with outliers depicted by small circles outside the box-whiskers plot, respectively. If the black-bold line (median) is closer to the 25th

percentile then the distribution was positively skewed, negatively skewed if the black-bold line is closer to the 75th percentile and uniformly distributed if the distance from black-bold line to the 25th percentile is equal to the distance from the black-bold line to the 75th percentile. Species with only one individual tree in the park are depicted by a single black-bold line.

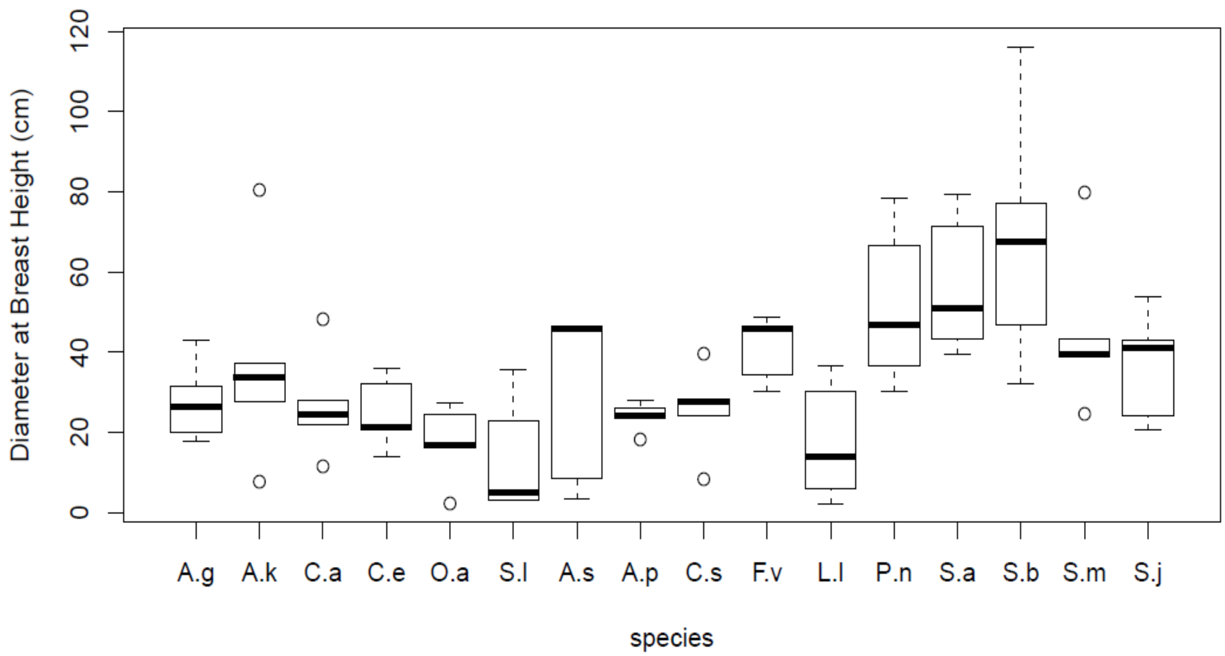

Figure 12: Distribution of diameter at breast height for the trees in Thokoza Park.

Where A.g; *Acacia galpinii*, A.k; *Acacia karroo*, C.a; *Celtis africana*, C.e; *Combretum erythrophyllum*, O.a; *Olea africana*, S.l; *Searsia lancea*, *Acacia sieberiana*, *Acer palmatum*, C.s; *Celtis sinensis*, *Franxinus velutina*, *Ligustrum lucidum*, *Populus nigra*, *Salix alba*, *Salix babylonica*, *Schinus molle* and *Sophora japonica*. The lowest whisker, lowest box margin, 'black-bold line', highest box margin and the highest whiskers represent the smallest diameter at breast height, the 25th percentile, median, 75th percentile and the largest diameter at breast height with outliers depicted by small circles outside the box-whiskers plot, respectively. If the black-bold line (median) is closer to the 25th percentile then the distribution was positively skewed, negatively skewed if the black-bold line is closer to the 75th percentile and uniformly distributed if the distance from black-bold line to the 25th percentile is equal to the distance from the black-bold line to the 75th percentile.

Figure 11 describes the distribution of diameter at breast height for the tree species in Petrus Molefe Park. *Acacia galpinii*, *Celtis africana*, *Combretum erythrophyllum*, *Olea africana* and *Celtis sinensis* had a positively skewed distribution. The three species namely, *Searsia lancea*, *Searsia pendulina* and *Platanus acerifolia* had a negatively skewed distribution. In contrast, Figure 12 shows the distributions of diameter at breast height in Thokoza Park. The distribution of diameter at breast height for *Celtis africana*, *Combretum erythrophyllum*, *Olea africana*, *Searsia lancea, Acer palmatum*, *Ligustrum lucidum*, *Populus nigra*, *Salix alba* and *Schinus molle* was positively skewed. Further, the boxplots indicate a negatively skewed distribution for *Acacia galpinii*, *Acacia karroo, Celtis sinensis*, *Franxinus velutina*, *Salix babylonica* and *Sophora japonica*.

Positively skewed distributions imply that trees used most of their photosynthetic gain preferentially for increase in tree diameter, while negatively skewed distribution suggest less photosynthetic gain used for tree diameter increase and more for tree height. The high variance in diameter at breast height within trees of the same species and different species may be explained by different factors particularly with regard to tree age, soil and topographic properties.

4.3. Descriptive statistics of tree height

In comparison to diameter, the variance of tree height was lower for both species in Petrus Molefe Park and Thokoza Park. However, statistical results indicated that there was a significant difference (F values; 6.02 > F critical; 1.85 for Petrus Molefe Park and F values; 111.95 > F critical; 1.70 for Thokoza Park) between the mean tree height of different tree species within each park. Trees in Thokoza Park had a greater difference among the means than the trees in Petrus Molefe Park suggesting that the growth rate or increase in tree height varied significantly in older trees (Thokoza Park) than in the younger trees (Petrus Molefe Park). Figure 13 shows size distribution of tree height for Petrus Molefe Park. Tree height for the species estimated to be seven years old ranged from 0.60 to 5.80 m for non-outliers, with *Combretum erythrophyllum* and *Celtis africana* having the lowest and greatest tree heights, respectively. *Acacia galpinii*, *Searsia lancea* and *Celtis sinensis* are described by a positively skewed distribution, while *Celtis africana*, *Combretum erythrophyllum*, *Searsia pendulina* and *Platanus acerifolia* had a negatively skewed distribution. In contrast, Figure 14 shows the variance and distribution of tree height for Thokoza Park. Tree height ranged from 1.70 to 25.10 (m) for non-outliers with *Ligustrum lucidum* and *Populus nigra* having the lowest and greatest tree heights, respectively. Overall, a comparison between Figures 11, 12, and 13 and 14 suggest that even though there was variance in diameter at breast height and tree height within trees of the same and different species, the variance in diameter at breast height was greater than the variance in tree height.

This distribution tendency may suggest that the trees used most of their photosynthetic gain preferentially in tree diameter growth than tree height growth.

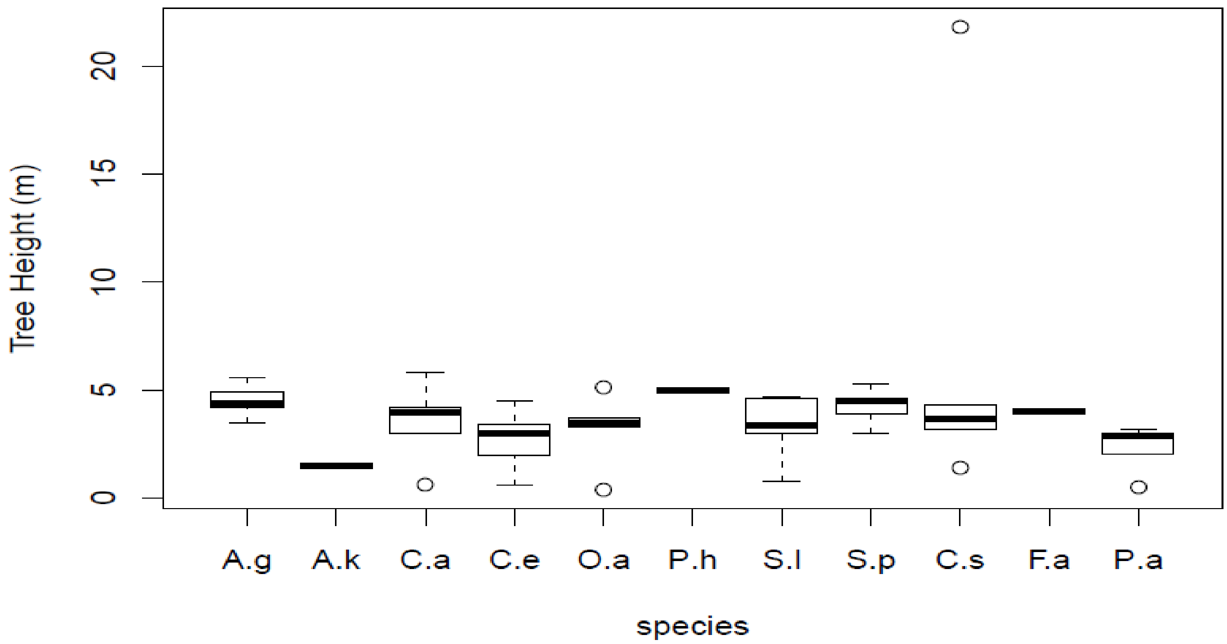

Figure 13: Distribution of tree height for the trees in Petrus Molefe Park.

Figure 13, showing the distribution of tree height for tree species in Petrus Molefe Park (*Franxinus americana* estimated to be 30 years old is not shown). Where, A.g; *Acacia galpinii*, A.k; *Acacia karroo*, C.a; *Celtis africana*, C.e; *Combretum erythrophyllum*, O.a; *Olea africana*, P.h; *Podocarpus henkelii*, S.l; *Searsia lancea*, S.p; *Searsia pendulina*, C.s; *Celtis sinensis*, F.a; *Franxinus americana* and P.a; *Platanus acerifolia*. The lowest whisker, lowest box margin, 'black-bold line', highest box margin and the highest whiskers represent the smallest tree height, the 25th percentile, median, 75th percentile and the highest tree height with outliers depicted by small circles outside the box-whiskers plot, respectively. If the black-bold line (median) is closer to the 25th percentile then the distribution was positively skewed, negatively skewed if the black-bold line is closer to the 75th percentile and uniformly distributed if the distance from black-bold line to the 25th percentile is equal to the distance from the black-bold line to the 75th percentile. Species with only one individual tree in the park are depicted by a single black-bold line.

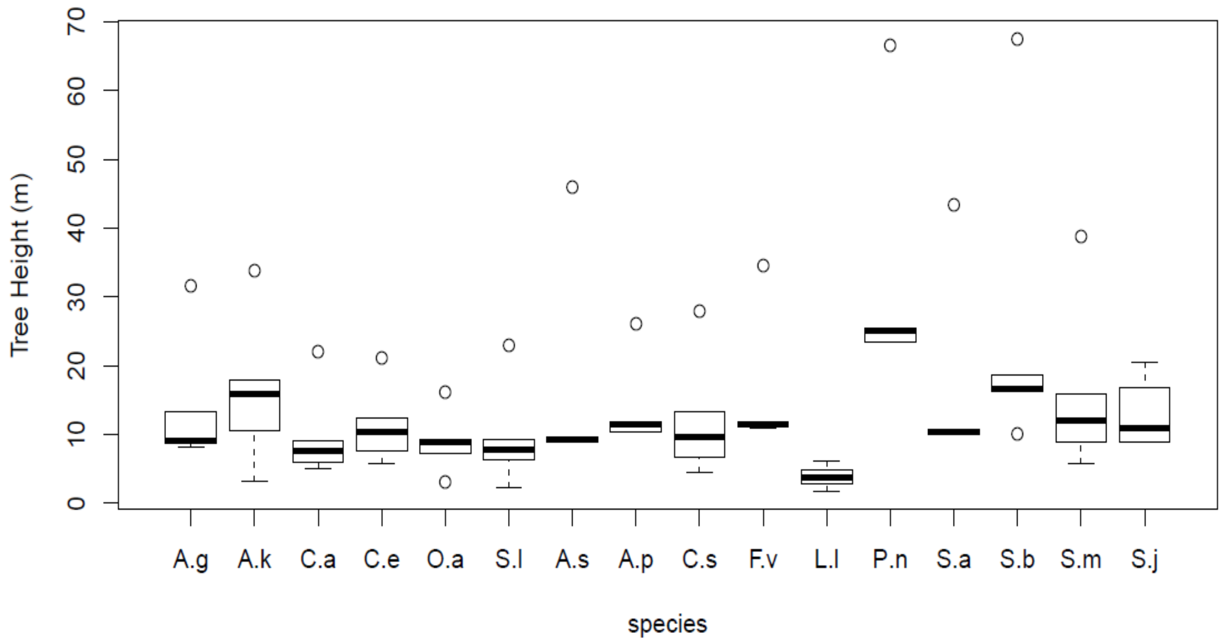

Figure 14: Distribution of tree height for the trees in Thokoza Park.

Where A.g; *Acacia galpinii*, A.k; *Acacia karroo*, C.a; *Celtis africana*, C.e; *Combretum erythrophyllum*, O.a; *Olea africana*, S.l; *Searsia lancea*, *Acacia sieberiana*, *Acer palmatum*, C.s; *Celtis sinensis*, *Franxinus velutina*, *Ligustrum lucidum*, *Populus nigra*, *Salix alba*, *Salix babylonica*, *Schinus molle* and *Sophora japonica*. The lowest whisker, lowest box margin, 'black-bold line', highest box margin and the highest whiskers represent the smallest tree height, the 25th percentile, median, 75th percentile and the highest tree height with outliers depicted by small circles outside the box-whiskers plot, respectively. If the black-bold line (median) is closer to the 25th percentile then the distribution was positively skewed, negatively skewed if the black-bold line is closer to the 75th percentile and uniformly distributed if the distance from black-bold line to the 25th percentile is equal to the distance from the black-bold line to the 75th percentile.

4.4. Correlation between diameter at breast height and above-ground biomass

The correlation between above-ground biomass and diameter at breast height was analysed for the five dominant species in Petrus Molefe Park namely, *Celtis africana*, *Celtis sinensis*, *Combretum erythrophyllum*, *Olea africana*, and *Searsia lance* in contrast to trees of the same species in Thokoza Park. The scatter plots indicate that there was a strong positive correlation between diameter at breast height and above-ground biomass (R^2; 0.79 to 0.91 for trees in Petrus Molefe Park and R^2; 0.91 to 1 for Thokoza Park). Figures 15a to 19b indicate that the correlation was a non-linear (exponential growth) between diameter at breast height and above-ground biomass. The slope was less steep for the younger species in Petrus Molefe Park than for the older tree species in Thokoza Park. This implies that with age, above-ground biomass increased more rapidly with diameter at breast height.

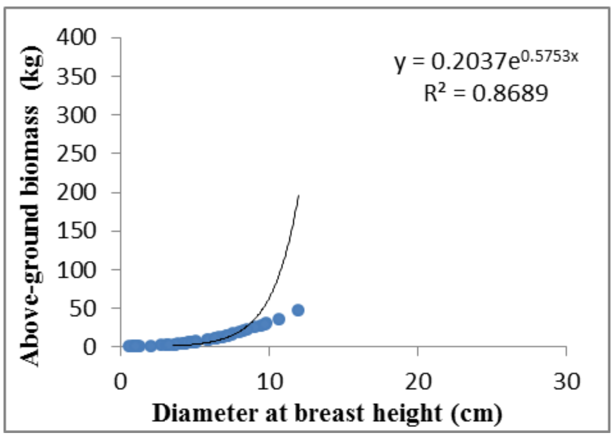

Figure 15a: *Celtis africana*, correlation between Diameter at breast height and Above-ground biomass for the 7 year old trees in Petrus Molefe Park.

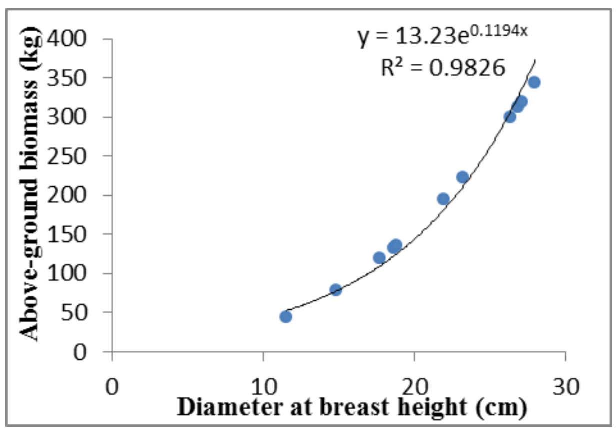

Figure 15b: *Celtis africana*, correlation between Diameter at breast height and Above-ground biomass for the 25 year old trees in Thokoza Park.

Figure 15a and 15b: Contrast between seven year old and 25 year old trees, showing the correlation between Above-ground biomass and Diameter at breast height for *Celtis africana*.

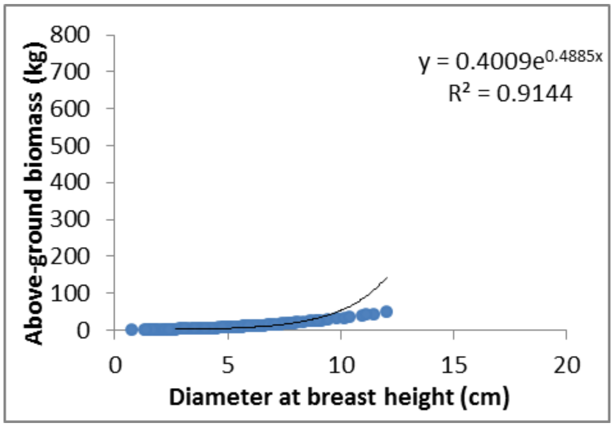

Figure 16a: *Celtis sinensis*, correlation between Diameter at breast height and Above-ground biomass for the 7 year old trees in Petrus Molefe Park.

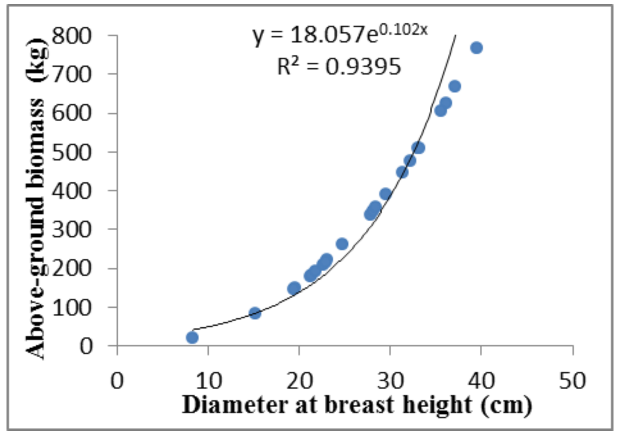

Figure 16b: *Celtis sinensis*, correlation between Diameter at breast height and Above-ground biomass for the 25 year old trees in Thokoza Park.

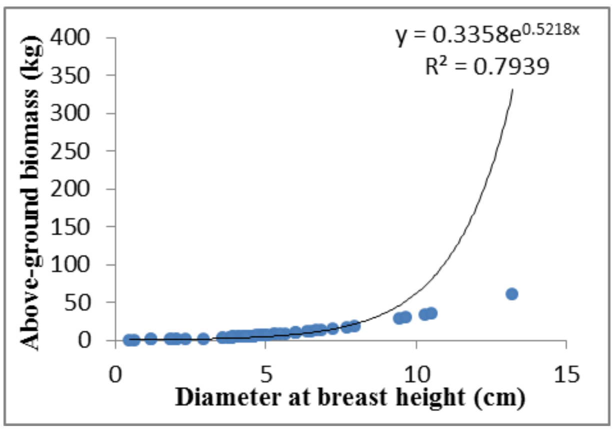

Figure 17a: *Combretum erythrophyllum*, correlation between Diameter at breast height and Above-ground biomass for the 7 year old trees in Petrus Molefe Park.

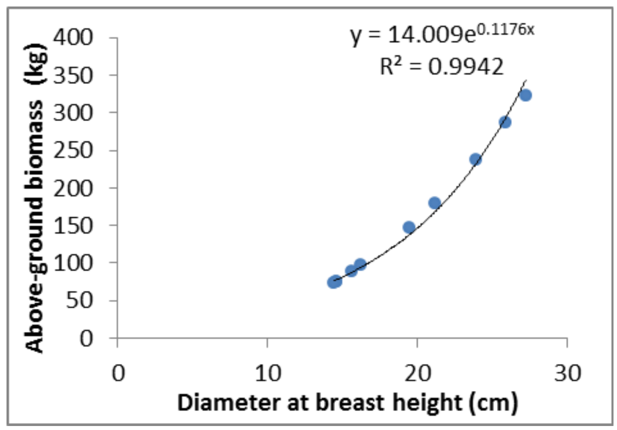

Figure 17b: *Combretum erythrophyllum*, correlation between Diameter at breast height and Above-ground biomass for the 25 year old trees in Thokoza Park.

Figure 16a and 17b: Contrast between seven year old and 25 year old species, showing the correlation between Above-ground biomass and Diameter at breast height for *Celtis sinensis* and *Combretum erythrophyllum*.

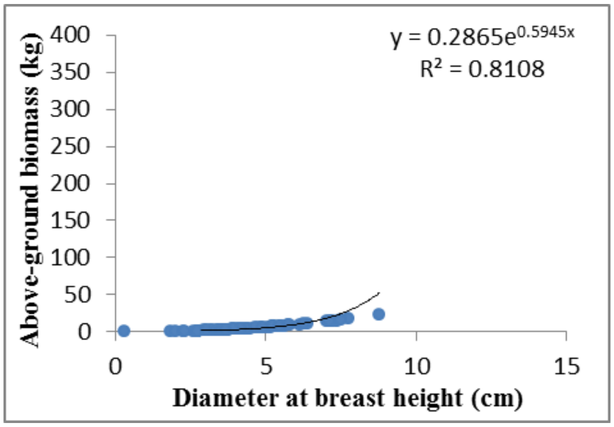

Figure 18a: *Olea africana*, correlation between Diameter at breast height and Above-ground biomass for the 7 year old trees in Petrus Molefe Park.

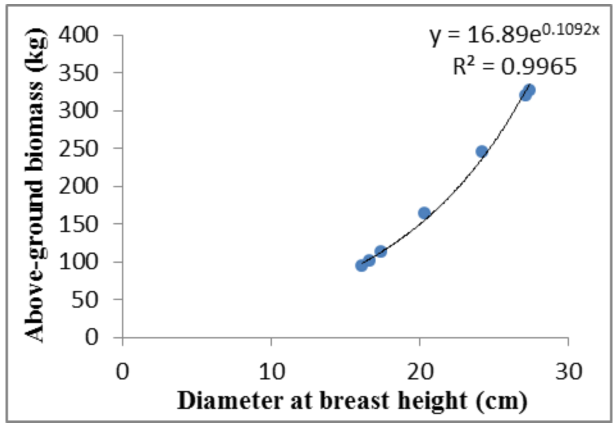

Figure 18b: *Olea africana*, correlation between Diameter at breast height and Above-ground biomass for the 25 year old trees in Thokoza Park.

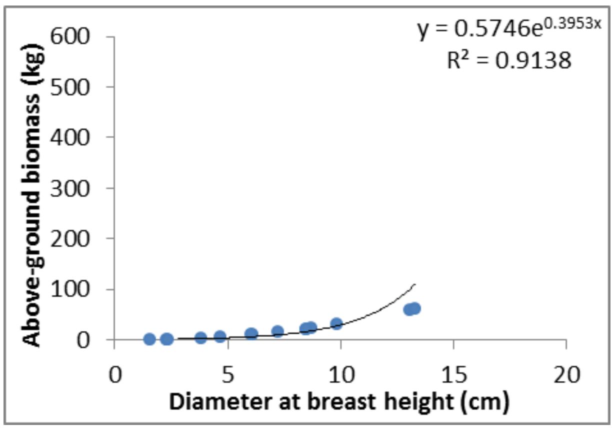

Figure 19a: *Searsia lancea*, correlation between Diameter at breast height and Above-ground biomass for the 7 year old trees in Petrus Molefe Park.

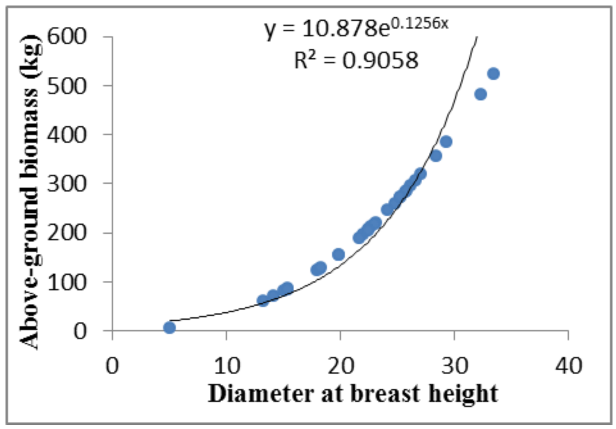

Figure 19b: *Searsia lancea*, correlation between Diameter at breast height and Above-ground biomass for the 25 year old trees in Thokoza Park.

Figure 18a to 19b: Contrast between seven year old and 25 year old species, showing the correlation between Above-ground biomass and Diameter at breast height for *Olea africana* and *Searsia lancea*.

4.5. Correlation between diameter at breast height and tree height

The correlation between tree height and diameter at breast height was also analysed for the five dominant species in Petrus Molefe Park namely, *Celtis africana*, *Celtis sinensis*, *Combretum erythrophyllum*, *Olea africana*, and *Searsia lancea* in contrast to trees of the same species in Thokoza Park. The coefficient of determination ranged from R^2; 0.29 to 0.84 for tree species in Petrus Molefe Park and R^2; 0.21 to 0.83 for tree species in Thokoza Park. Figures 20a to 24b indicate that with age, tree height increased logarithmically with diameter at breast height. This means that trees increased rapidly in height when young, but because of the coordination and regulation of photosynthetic gain allocation between stem diameter and tree height growth, increase in tree height tapered off and became less steep.

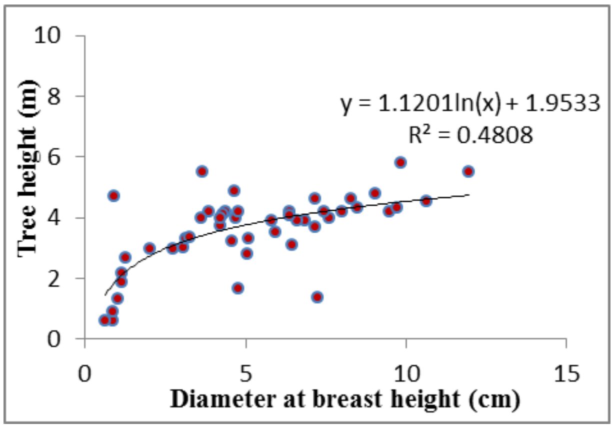

Figure 20a: *Celtis africana*, correlation between Diameter at breast height and tree height for the 7 year old trees in Petrus Molefe Park.

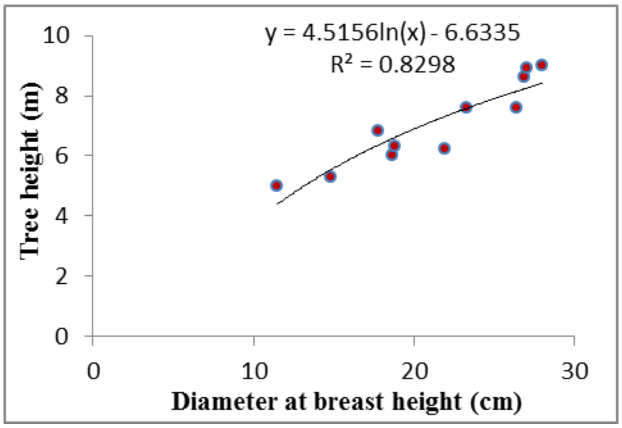

Figure 20b: *Celtis africana*, correlation between Diameter at breast height and tree height for the 25 year old trees in Thokoza Park.

Figure 20a and 20b: Contrast between seven year old and 25 year old species, showing a non-linear (logarithmic) correlation between tree height and Diameter at breast height for *Celtis africana*.

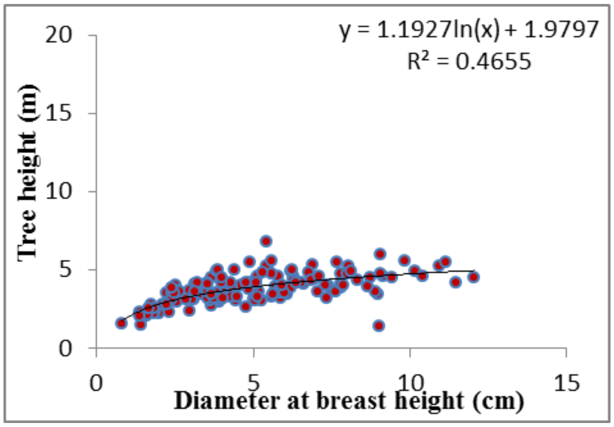

Figure 21a: *Celtis sinensis*, correlation between Diameter at breast height and tree height for the 7 year old trees in Petrus Molefe Park.

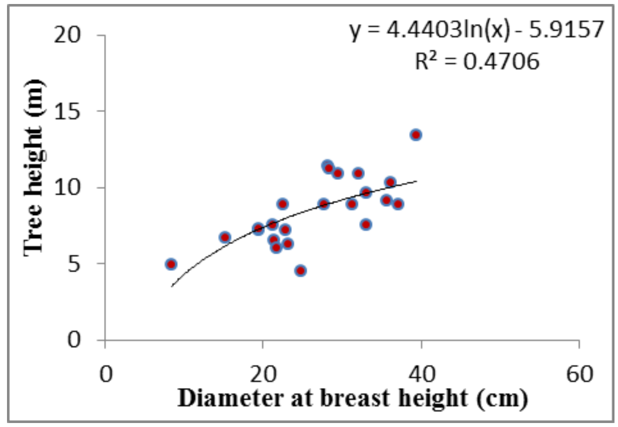

Figure 21b: *Celtis sinensis*, correlation between Diameter at breast height and tree height for the 25 year old trees in Thokoza Park.

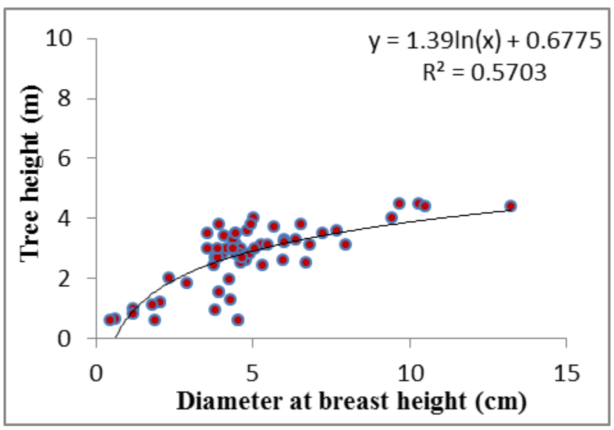

Figure 22a: *Combretum erythrophyllum*, correlation between Diameter at breast height and tree height for the 7 year old trees in Petrus Molefe Park.

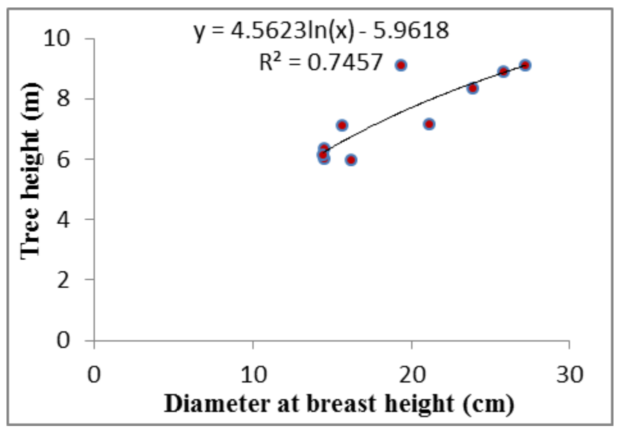

Figure 22b: *Combretum erythrophyllum*, correlation between Diameter breast height and tree height for the 25 year old trees in Thokoza Park.

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Figure 21a to 22b: Contrast between seven year old and 25 year old species, showing a non-linear (logarithmic) correlation between tree height and Diameter at breast height for *Celtis sinensis* and *Combretum erythrophyllum*.

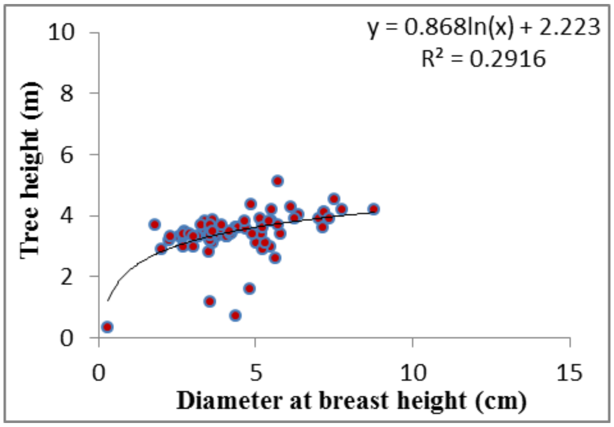

Figure 23a: *Olea africana*, correlation between Diameter at breast height and tree height for the 7 year old trees in Petrus Molefe Park.

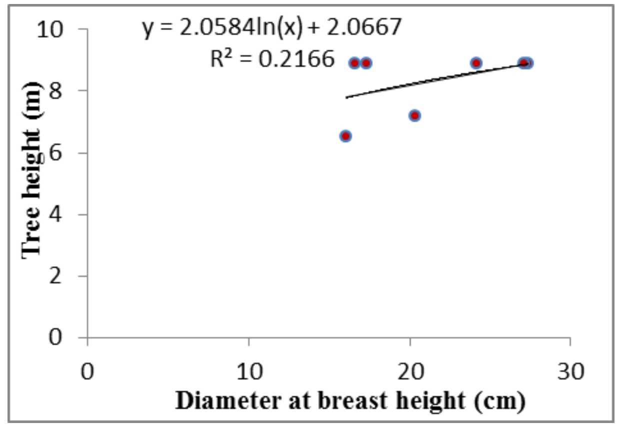

Figure 23b: *Olea africana*, correlation between Diameter at breast height and tree height for the 25 year old trees in Thokoza Park.

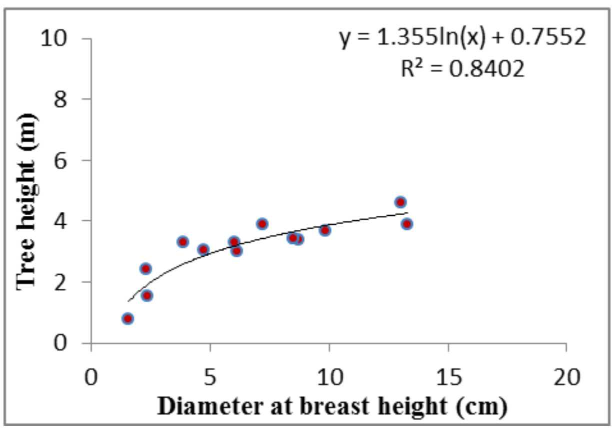

Figure 24a: *Searsia lancea*, correlation between Diameter at breast height and tree height for the 7 year old trees in Petrus Molefe Park.

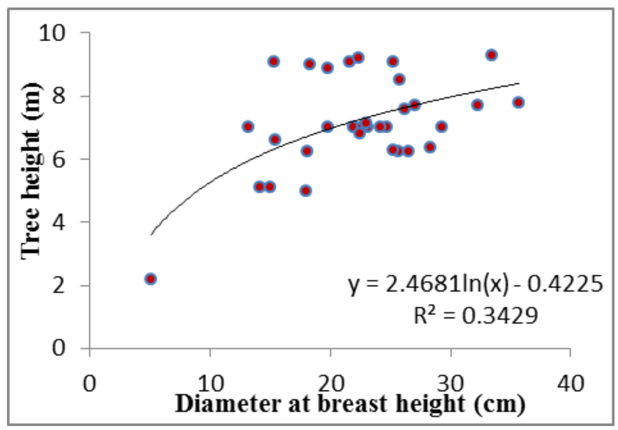

Figure 24b: *Searsia lancea* , correlation between Diameter at breast height and tree height for the 25 year old trees in Thokoza Park.

Figure 23a to 24b: Contrast between seven year old and 25 year old species, showing a non-linear (logarithmic) correlation between tree height and Diameter at breast height for *Olea africana* and *Searsia lancea*.

CHAPTER FIVE

5. Discussion

The Greening Soweto Project is not only about transforming the dry, dusty streets and landfills that previously characterised Soweto township to beautiful green spaces, (Johannesburg City Parks Online 2012), but also demonstrates that the tree planting project has the potential to contribute to national and international climate change mitigation initiatives (Stoffberg *et al*., 2010; McGranahan *et al*., 2005). As a result, monitoring and estimating above-ground urban trees biomass and carbon stocks have become an important requirement for the ecological economics agenda (Spash, 2012; Douai, 2009). This discussion includes the topics, climate change: the need for carbon sequestration, estimating tree biomass by using allometric equations, biomass and carbon stored in Petrus Molefe Park, and Thokoza Park, the economic value of stored carbon, and cost benefit analysis: measuring the performance of the Greening Soweto Project.

5.1. <u>Climate change: The need for carbon sequestration</u>

The Earth's surface temperatures have risen by 0.8°C in the last 100 years and since 1975, the recorded rate of temperature increase has been 0.15°C per decade (Rockström *et al.*, 2009; IPCC 2007; IPCC 2001;). Exacerbated by anthropogenic activities such as the burning of fossil fuel (e.g. coal), land-use change, deforestation and degradation, the global surface temperature is predicted to rise by 1.5 to 5.8°C by the end of the twenty first century (2090 to 2099) (Rockström *et al.*, 2009). These changes have caused notable shifts in ecosystem function (Kump, 2011; Schaffer and Carpenter, 2003). To ameliorate the adverse effects of these perturbations, three Clean Development Mechanism (CDM) strategies, namely reducing global energy use, developing low carbon fuel and carbon sequestration (e.g. afforestation and reforestation) have been proposed as viable approaches to the global warming and climate change (Barbosa *et al*., 2007). This study was underpinned by the CDM strategy where carbon sequestration is accomplished through fixation of CO_2 and conversion to urban tree biomass (Jansson *et al*., 2010; Pretzsch, 2009).

Since the Industrial Revolution, the price of energy and production has not reflected the related costs of negative externalities such as emissions of CO_2. The failure by the international market to account for the full associated cost of producing goods and services have led to present challenges of climate change. For instance, if the value and scarcity of forest ecosystems services (e.g. carbon sequestration) are not guided by the concept of economic value, forests such as urban trees are often underappreciated with subsequent misuse, deforestation and degradation. Therefore, the carbon policy was formulated based on the concept that negative externalities from industrial production be taxed at an equivalent social cost (World Business Council for Sustainable Development 2013). Converting the amount of carbon sequestrated by trees to economic value involves quantifying tree biomass and monitoring the changes in carbon stocks (Roxburg *et al*., 2006).

Concurrent with the emerging carbon market in South Africa (Department of National Treasury 2013), Johannesburg City Parks identified the need to know the extent of carbon sequestrated by the trees in Petrus Molefe Park and Thokoza Park in Soweto and the associated economic value. This would allow extrapolation of the methodology and procedure used in this study to a large area in Soweto where urban trees had been planted. This study was limited to only two sites therefore, interpretation and extrapolation should be done with caution. Monitoring, measuring and reporting of these ecosystems services are critical in guiding decisions on planning, management and conservation of urban trees (Hammond *et al*., 1995). Availability of such information provides an opportunity for organisations to generate revenue. For instance, Johannesburg City Parks could qualify for financial incentives provided through the United Nations-Reducing Deforestation and Degradation Programme (UNREDD) and the World Bank to support organisations which increase forest cover through carbon sequestration and demonstrate environmental, social and economic sustainability (UNFCCC 2011; UNREDD 2010; World Bank 2005).

5.2. Estimating tree biomass by using allometric equations

The study in Petrus Molefe Park and Thokoza Park examined the allometric relations of above-ground biomass against stem diameter at breast height. Diameter at breast height was the only variable used in the Tietema (1983) allometric equation. The equation was appropriate for the study because it is a general equation and a power (e.g. of the form ax^n) based model developed and validated from 14 different species (Zianis and Mencuccini, 2004; Tietema, 1993). The estimated above-ground biomass was plotted against diameter at breast and the scatter plots indicating a strong positive correction (R^2; 0.79 to 0.91 for trees in Petrus Molefe Park and R^2; 0.91 to 1 for Thokoza Park) suggested that diameter at breast height for the two parks was closely associated with above-ground biomass (Figure 15a-19b). Because the Tietema (1993) equation does not include tree height in the estimation of biomass, the relationship between diameter at breast height and tree height was established.

The scatter plots indicated that tree height increased logarithmically with diameter at breast height (Figure 20a-24b). The relationship suggested that trees increased rapidly in height when young and tapered off with increase in diameter at breast. This is in agreement with the study of carbon allocation by Rogers *et al*., (1996) that observed that accretion of carbon metabolites and subsequent increase in tree height and/ or tree diameter (girth) often happen in a coordinated way with an implication of unequal partitioning of photosynthetic gain among plant tissues. The phenomenon of carbon allocation dictates that trees maintain the ability to unequally alter the allocation of carbon metabolites in response to changing environmental conditions (Rogers *et al*., 1996).

5.3. Biomass and carbon stored in Petrus Molefe Park and Thokoza Park

The trees estimated to be about seven years old and the two individual trees estimated to be greater than 30 years old in the 9.3 hectares of Petrus Molefe Park had an average tree density of 44.6 individual trees per hectare. Whereas the trees estimated to be about 25 years old with some trees estimated to be over 30 years old in the 3.3 hectare portion of Thokoza Park had an average tree density of 88.3 individual trees per hectare. As a result of the low tree density in both parks, the trees were well spaced (open canopy) with measurable stem diameter and tree height for all individual trees (Hunter *et al*., 2013). The measured characteristics of the 414 individual trees in

Petrus Molefe Park and the 294 trees in Thokoza Park showed that both diameter at breast height and tree height were highly variable between individual trees. Values for diameter at breast height ranged from 0.4 to 17.6 cm and 0.6 to 5.8 m for height for Petrus Molefe Park, and 2.1 to 116.2 cm and 1.7 to 25.1 m for Thokoza Park (Figure 11 to14). Positively skewed distribution of diameter at breast height suggested that species used most of the photosynthetic gain for stem diameter increase and less for tree height, while negatively skewed indicated that less of the photosynthetic gain was used for diameter increases rather than tree height. This variability could be attributed to different trees and species and their ability to source deep water resources. For instance, younger trees may only have access to limited soil water in the upper soil layers, while older trees could tap deeper water sources. This allows the older trees to fix greater amounts of atmospheric CO_2 than the younger trees (Verweij *et al*., 2011). The scope of this research report was limited to measurements of tree diameters and heights. No other measurements were taken and this limits the associated interpretation and discussion of the research.

The Net Ecosystem Productivity or the total amount of photosynthetic gain converted to above-ground biomass and carbon stocks by the 414 individual trees in Petrus Molefe Park was 7.45 tonnes and 3.35 tonnes, respectively. The trees estimated to be about seven years old comprising 398 individual trees contributed 3.9 tonnes (53% for the eight indigenous species) and 0.06 tonnes (0.8% for the three non-indigenous species) to the total above-ground biomass, respectively. The two individual trees estimated to be greater than 30 years old accumulated higher above-ground biomass of 3.5 tonnes which represented 46.6% of the total above-ground biomass. These values illustrated that indigenous species can contribute to carbon sequestration. Therefore, it is recommended that further research is conducted on seed germination and seedling establishment, and its management once planted (e.g. watering), which are often identified as problem areas when using indigenous species. It would also be important to select fast-growing species (CSIR 2011; Cronk and Fuller, 2001).

The contrasting site, Thokoza Park with 294 trees accumulated greater above-ground biomass of 205.76 tonnes and 92.59 tonnes of carbon stocks. Most of the indigenous species were estimated to about 25 years old, with an above-ground biomass of 52.23 tonnes, contributing 25.3% to the total above-ground biomass. The non-indigenous species estimated to be over 30 years old accumulated 153.53 tonnes representing 74.6% of the total above-ground biomass in the park. The intention of the Greening Soweto Project was to emphasise the use of indigenous species. This is reflected in Petrus Molefe Park where most of the species are indigenous and account for 53% of the above-ground biomass. The introduction of policies like the Forest Act 1998 meant to curtail the spread of alien invasive plants have significantly contributed to the promotion of indigenous species (van Wigen *et al*.,2012; van Wilgen and Moran, 2007). However, trees over 30 years old were mostly non-indigenous species as less care was given to which species should be planted during the apartheid regime. Overall, the contrasting values of Thokoza Park suggested that the ability of trees to fix atmospheric CO_2 and convert the photosynthetic gain to above-ground biomass and carbon stored increases with age. This is consistent with the findings of Peichl and Arain (2006) in a study conducted on four age classes of mixed tree species in Southern Ontario, Canada. The species aged 2 sequestrated an average of 0.2 tonnes of carbon per hectare (tC/ha), 30.1 tC/ha for the 15 year old species, 44.2 tC/ha for the 30 year old species and 82.6 tC/ha for the 65 year old species.

An average of 27.80 (total carbon stored/size of park) tonnes of carbon per hectare (tC/ha) in Thokoza Park is within the reported averages from other urban greening projects in USA, China, Indonesia and Kenya. The average carbon stored in the trees ranged from 14.19 to 35.74 tC/ha for ten cities in the USA, 45.39 tC/ha for Beijing, between 180 to 250 tC/ha for the Berau district in Kalimantan and about 13.55 tC/ha for Gazi Bay in the south of Mombasa (CIFOR Online 2015; Kipkorir araap Sigi Lang'at, 2013; Nowak and Crane, 2002). Therefore, the estimated average of 0.36 tonnes of carbon per hectare for the trees in Petrus Molefe Park is relatively less and only beginning to demonstrate signs of future potential. Despite tree age being the main factor accounting for the difference, Petrus Molefe Park had relatively lower tree density. For instance, the average tree density for Petrus Molefe Park of 44.56 (total number of individual trees/size of park) trees per hectare (trees/ha) was at the low end than a reported average of 36 to 276 trees/ha for ten cities in USA, 79 trees/ha for Beijing, between 200 to 800 trees/ha for the Berau district and between 1000 to over 1, 500 trees/ ha for Gazi Bay (CIFOR Online 2015; Pachaiyappan, 2013; Yang *et al*., 2005). These values corresponded to the annual precipitation of 1,300 mm, 630 mm, and between 1800 to 3000 mm, and 1000 to 1600 mm, respectively. This relationship suggests that initial tree stocking should take account of the local annual precipitation, otherwise trees growing in close proximity may be water stressed as they compete for the available soil water. An imbalance between tree density and local annual precipitation often results in slow growth and mortality. However, despite Petrus Molefe Park and Thokoza Park experiencing the same average precipitation (ranging from 548±74 to 817±55 mm), the tree density for Thokoza Park was twice (88.29 trees per hectare) that of Petrus Molefe Park. This may indicate that there is an opportunity to optimise the long term carbon sequestration in Petrus Molefe Park by increasing tree density at the park.

5.3.1. The economic value of the stored carbon

Estimating the economic value of carbon sequestration is important in managing the interaction between urban trees and urban habitability and sustainability (Howarth and Farber, 2002). Economic valuations are also useful in demonstrating quantitative environmental conditions, the status of urban trees and the potential of tree planting projects in the carbon offset market. However, converting forest ecosystem services (such as carbon sequestration, filtering air, regulating microclimate, reducing wind speed, recreation and amenity etc.) into economic value is a new concept in emerging carbon offset markets, with limited frameworks and procedures. In this study, the carbon stored in Petrus Molefe Park and Thokoza Park were converted to economic values using R440.40 per tonne of carbon which is based on the proposed carbon price of R120 per tonne of CO_2 equivalent (Department of National Treasury 2013). The proposed carbon dioxide price was converted to carbon price using the carbon dioxide to carbon atomic ratio of 3.67. Therefore, the total economic value of carbon stored by the trees in Petrus Molefe Park was R1,475, while Thokoza Park had R40,777. Because the economic values were estimated from the total sequestrated carbon from the two parks, these values might become more significant with time as the trees age.

Under the Kyoto Protocol, tree planting projects that are eligible for the carbon offset market should firstly be tree planting projects that involve transformation of formerly degraded landscape to green spaces. Secondly, the greening projects should cover an area greater than 0.2 hectares with the tree potential height of more than two meters and crown cover at least 20% of the area (Johnson and Coburn, 2010). Evidence from other tree planting projects in Africa (Table 4) and the findings from the Greening Soweto Project suggest that under the emerging carbon market, Johannesburg City Parks can directly play an active role in mitigating climate change, developing urban habitability and sustainability while generating revenue through off- setting carbon emissions.

Table 3: Economic benefits of carbon offsets from other tree planting projects in Africa.

Country	Area	Implementing Agency	Carbon offsets	Revenue (Incentive from REDD programme)
Benin	126,700 ha	National Government	0.14 MtC	US$2.5 million
Tanzania	6,500 ha	Green Resources Busoga	0.63 MtC	US$500 million for four years
Uganda	9,000 ha	New Forests Company	0.07 MtC	US$12.85 million
South Africa	Extrapolation of the methodology used for Petrus Molefe Park and Thokoza Park to a large area in Soweto	Johannesburg City Parks	3.35 tC (9.29 ha) over an average of 8 years and 92.59 tC (3.33 ha) over an average of 25 years	Opportunity

Note: Mt is million tonnes of carbon, while tC is tonnes of carbon, ha is hectares, REDD is Reducing emission from Deforestation and Forest Degradation (source: data from Jindal *et al*., 2008 with inclusion of the Greening Soweto Project).

The first carbon market scheme was implemented in New South Wales in 2003. The price for carbon trading of one abatement certificate (equivalent to one tonne of CO_2-e) was $8 to $10 in 2004, $14 in 2006 and $5 in 2009. An abatement certificate is the document that define an organisations permissible level of emission and the action taken to reduce GHG emissions based on the capacity of the sink (action or process that removes GHG from the atmosphere) (DEA and GIZ 2014). The scheme was aimed at reducing greenhouse gases associated with electricity generation. Through purchasing of abatement certificates from accredited forest managers or reforestation projects, primary electricity producers were able to offset their emissions. This scheme illustrated the economic potential of urban tree planting projects for carbon sequestration (Johnson and Coburn 2010). Further, evidence from urban forest projects in the United States demonstrates that urban trees could serve as a viable economic market. Nowak and Crane (2002) reported that urban trees in the United States fixed about 22.8 million tonnes of atmospheric carbon and $460 million in revenue was realised from selling carbon offsets in 2002. Offsets are Clean Development Mechanisms (CDM) registered projects where countries are allowed to invest in projects that reduce GHG emissions done elsewhere but incentivized from direct capital investment and purchase of abatement certificates by developed countries (World Bank, 2005). In this context, urban tree planting projects have continued to grow in the United States, presently maintaining over 4 billion individual trees in parks, streets and numerous public and privately owned places and Metropolitan areas countrywide (Nowak and Crane, 2002). Similarly, Johannesburg City Parks like many others has benefited from tree planting projects aimed at offsetting the carbon footprint of major international events (e.g. United Nations Climate Change Conference, COP 17 in Durban, South Africa and allocation of 'Beautification Fund' for the 2010 FIFA World Cup soccer event).

5.4. Cost benefit analysis: Measuring performance of the Greening Soweto Project

Cost benefit analysis in urban greening projects is necessary when assessing the economic value of the sequestrated carbon with the cost of planting trees. The findings of this study indicated that the net economic value of carbon stored or the total economic value was significantly less than the total cost of planting trees. In Petrus Molefe Park, the net economic value of the above-ground stored carbon as at July 2014 was R-495,325. The contrasting trees in Thokoza had a net economic of R-312,023. This means that the economic value of carbon sequestrated by the Greening Soweto Project relative to the cost of planting trees is currently negative. The project is at an early stage and showing promise. With sustainable conservation and management actions over time, the economic value of carbon stored could improve and balance the cost of planting the trees.

However, measuring the performance of the Greening Soweto Project should not only be based on the economic value of stored carbon, but should account for the social and environmental contribution and benefits as shown in Figure 25a and 25b (UNEP Online 2015; DEA and GIZ

2014; UNCED 1993). Such considerations are necessary for projects such as urban tree planting that provide multiple ecosystem services such as carbon sequestration, beautifying the landscape, recreation, amenity, providing shade, habitat for external biodiversity and filtering air etc. (Shackleton *et al*., 2013; Sundaram, 2011).

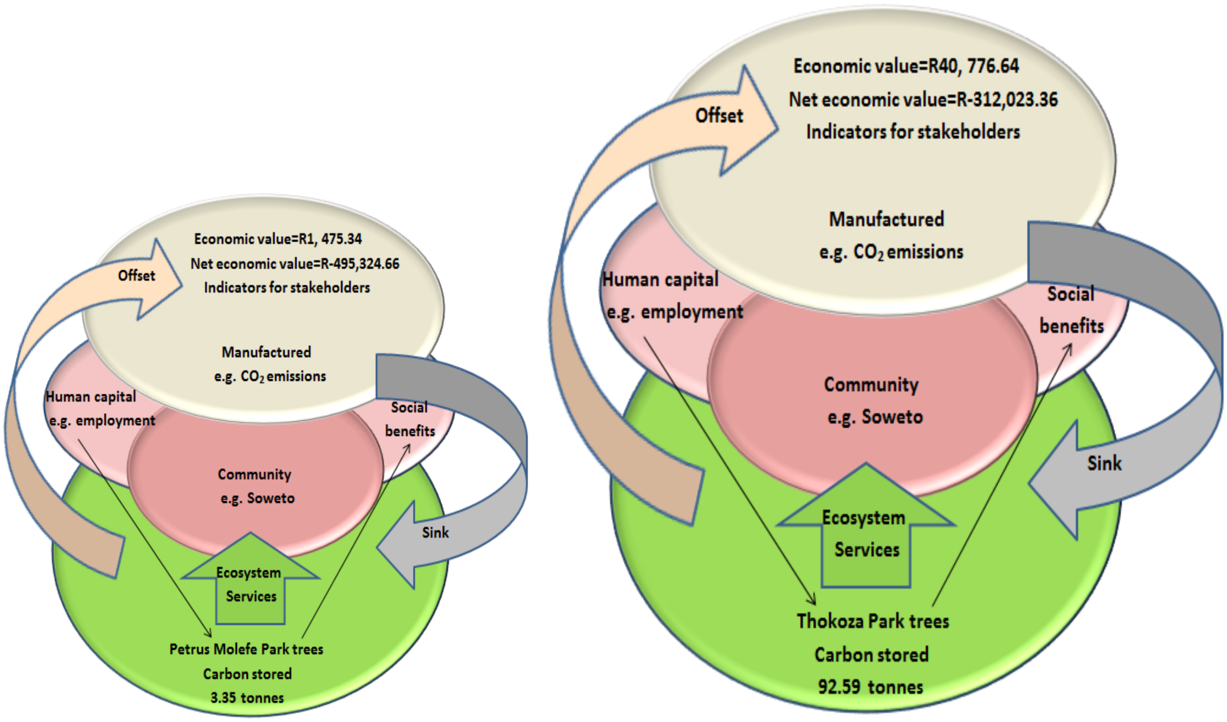

Figure 25a and 25b: Contribution of Greening Soweto Project to the social and environmental or ecosystem function of Soweto township.

The contribution of younger trees in Petrus Molefe Park was less than the older trees in Thokoza Park as depicted by the size of the models. The amount of carbon stored and the associated economic value and net economic value can be used as a qualitative indicator of the environmental condition of trees and a guide to decisions concerning planning, conservation and management actions.

This concept of sustainable development suggests that business or project performance should not be measured only by their economic benefits, but by the level of the environmental, social and economic integration (Norman and MacDonald, 2003). This principle has been accepted internationally where tree planting projects qualifying under the Reducing Deforestation and Degradation (REDD+) programme and are required to demonstrate their economic, social and environmental concerns and obligations. Demonstrating environmental concerns involves pricing urban tree ecosystem services so that the goods and services reflect the relative scarcity, importance and value of trees, while social concerns considers concerns of social justice and equity (Westpal, 2003). Contrary to the pre 1994 regime where some South Africans where zoned to reside in high density townships, while poorly serviced with little or no green spaces in what was known as the green divide, the ‘Greening Soweto Project’ has demonstrated sustainable development partly by fostering social justice and equity through urban tree planting in public places such as streets and parks (Howarth and Farber, 2002). Further, the Greening Soweto Project enhances the social benefits through direct and indirect employment creation (DEA and GIZ 2014; Stringer *et al*., 2006; Westpal, 2003). Direct employment includes tree planting, tree staking, and mulching of trees, while seasonal or indirect jobs involve pruning, pest and disease control and irrigating of trees etc. The economic, social and environmental benefits in promoting urban habitability and the potential of urban trees in mitigating global warming and climate change underscore the need to enhance national tree planting projects. This is consistent with the recommendation by Reynod (2012) that urban greening projects emphasising several economic, social and environmental objectives are much more likely to be successful than projects specialising in carbon sequestration alone.

This study was able to demonstrate carbon sequestration through the use of allometric equations subsequent to tree measurements. The techniques used can be taught to urban managers and municipal officials to use as part of monitoring and evaluation. This is important because tree planting projects for offsetting carbon footprint of major international events have other long term benefits. Further, the results of this study support earlier findings in South Africa’s Mitigation Potential Analysis (MPA) which was carried out by the National Department of Environmental Affairs in 2014. The MPA identified urban tree planting as a measure that can contribute to climate change mitigation. However, future studies should go further to include other social aspects, benefits and the value chain of tree planting project to help quantify the contribution to driving the green economy. This is important since the contribution of Agriculture, Forestry and Land Use (AFOLU) sector towards the green economy is overlooked or underestimated as a result is ranked the lowest after the Energy, Transport and Waste sectors.

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