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Urban green spaces enhance carbon sequestration and conserve biodiversity in cities of the Global South case of Kumasi, Ghana

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ABSTRACT

Urbanization has the propensity to alter ecosystems, enervate ecosystem function and possibly jeopardise human wellbeing. While adequate integration of nature into the city landscape can pragmatically ameliorate urban environmental challenges, particularly those related to climate change and ecosystem degradation, in the developing regions, especially in Africa, urban green spaces (UGS) are hardly planned for and their ecosystem services unquantified and hence misappropriated. This study analyses 1) the spatio-temporal dynamics and distributional equity, 2) carbon sequestration potential, and 3) biodiversity patterns of UGS in Kumasi metropolis, Ghana. Direct ecosystem assessment (inventory and survey) and remote sensing techniques were adopted in this study.

The vegetation cover of Kumasi is about 33 % and is declining fourfold faster in recent years (2009 – 2014) than previously (986 – 2001). Per capita UGS area for 2009 and 2014 are significantly correlated with the socio-economic conditions of submetropolis. The green area stores about 3758.1 Gg C: equivalent to 270±22 t C/ha per UGS cover or 125.7 ± 8 t C/ha for the entire study area in both soil and vegetation. Exactly 176 tree species in 46 families of both native and exotic origins occur in the city. Carbon stocks and species richness differ significantly across UGS types. Natural forest, public parks, cemeteries and institutional compounds stored more carbon in vegetation whereas soil organic carbon storage was highest in the home gardens, farmlands, plantations, and grasslands. The outer fringes of the city support more species and carbon stocks than the core urban area. Species and trait diversity are important drivers of urban ecosystem productivity (carbon storage). UGS species richness correlated strongly with vegetation carbon storage in the city.

UGS are carbon sinks and biodiversity reservoirs which can be relevant to climate change mitigation and adaptation as well as the overall wellbeing of urbanites. However, UGS cover is currently plummeting and is threatened by further urbanization processes including rise in population. Maintenance, expansion, and uniform distribution of green spaces in cities should be a priority for planners, national and local governments as well as traditional leaders. It is recommended that urban biodiversity and carbon stocks be integrated into national and regional biodiversity and carbon stock assessments in Africa.

URBAN GREEN SPACES ENHANCE CARBON SEQUESTRATION AND CONSERVE BIODIVERSITY IN THE GLOBAL SOUTH – CASE OF KUMASI, GHANA

KURZFASSUNG

Durch Verstädterung besteht die Tendenz, dass Ökosysteme verändert werden, die Funktion von Ökosystemen geschwächt wird und möglicherweise das menschliche Wohlergehen gefährdet wird. Während eine angemessene Integration von Grünflächen in die Stadtlandschaft bei der Bewältigung der städtischen ökologischen Herausforderungen, besonders in Bezug auf Klimawandel und die Beeinträchtigung des Ökosystems, pragmatisch helfen kann, werden in Entwicklungsgebieten, vor allem in Afrika, kaum städtische Grünflächen (urban green spaces - UGS) geplant. Des Weiteren werden die von UGS geleisteten Ökosystemdienstleistungen zumeist nicht beziffert und demnach in globalen Analysen nicht erfasst. Diese Studie analysiert 1) die räumlich-zeitliche Dynamik und das Verteilungsmuster, 2) das Potential von Kohlenstoffbindung und 3) die biologische Vielfalt und Funktion von UGS im städtischen Großraum von Kumasi, Ghana. In dieser Studie wurden Methoden zur direkten Bewertung des Ökosystems und Fernerkundungstechniken verwandt.

UGS in Kumasi umfassen z.Z. etwa 33 % des städtischen Großraum von Kumasi und diese Fläche schrumpfte in den letzten Jahren (2009 – 2014) viermal schneller als zuvor (1986 – 2001). Die pro Kopf Verteilung von UGS in Kumasi korreliert signifikant mit den dortigen sozioökonomischen Bedingungen. Die Grünflächen speichern etwa 3758,1 Gg Kohlenstoff; im Durchschnitt entspricht dies 270 ± 22 t Kohlenstoff / ha UGS oder 125,7 t Kohlenstoff / ha im gesamten Untersuchungsgebiet, sowohl in Form von Böden als auch Vegetation. Im Großraum Kumasi kommen 176 verschiedene Baumarten aus 46 heimischen und nicht-heimischen Familien vor. Kohlenstoffbestände und Artenvielfalt unterscheiden sich strak in Abhängigkeit des Typus von UGS. Reste natürlichen Waldbestandes, öffentliche Parks, Friedhöfe und Bäume auf dem Gelände von öffentlichen Institutionen speicherten mehr Kohlenstoff in der Vegetation, wobei der organische Kohlenstoffspeicher in privaten Gärten, auf Feldern, Plantagen und Grasflächen am höchsten war. Stadtrandgebiete haben eine höhere Biodiversität und speichern mehr Biomasse als der innenstädtische Bereich. Arten- und phenotypische Vielfalt haben einen grossen Einfluß auf die Funktion städtischer Ökosysteme. Das Ausmaß der Artenvielfalt in städtischen Grünflächen steht im engen Zusammenhang mit dem Kohlenstoffbestand in der städtischen Vegetation.

Städtische Grünflächen sind wichtige Kohlenstoffspeicher und Quellen der biologischen Vielfalt, die für die Vermeidung von und Anpassung an Klimawandelfolgen und das allgemeine Wohlergehen von Städten sehr relevant sind. Allerdings gefährdet das rapide Bevölkerungswachstum und die zunehmende Urbaniserung die existierenden städtischem Grünflächen in Afrika. Instandhaltung, Erweiterung und auch eine verbesserte und gerechtere Verteilung von städtischen Grünflächen sollten für Städteplaner, Landesregierungen, Lokalverwaltungen und traditionelle Führer eine Priorität darstellen.

LIST OF ACRONYMS AND ABBREVIATIONS

AGB	Aboveground biomass
AGC	Aboveground carbon
BA	Basal area
BGB	Belowground biomass
BGC	Belowground carbon
BS	Broken-stick model
C	Carbon
CA	Correspondence analysis
CBD	Convention on Biological Diversity
CI	Confidence Interval
DBH	Diameter at breast height (1.3 m above ground)
EF	Ecological footprint
ESS	Ecosystem services
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GI	Gini index
GS	Geometric series model
HDUZ	High density urban zone
HH	House hold
HQI	Housing Quality Index
ICT	Institutional Compound trees
KMA	Kumasi metropolitan assembly
KNUST	Kwame Nkrumah University of Science and technology
LDUZ	Low density urban zone
LN	LogNormal
NDVI	Normalized difference vegetation index
NIR	Near infra-red
PCA	Principal Component Analysis
R	Red
RMSE	Root mean square error
SDG	Sustainable development goals
SOC	Soil organic carbon
SOM	Soil organic matter
UGS	Urban green spaces
UN	United Nations
WRB	World resource base

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1 GENERAL INTRODUCTION

1.1 Background and problem statement

Urbanization is a major driver of global change: driving land use change, habitat loss, biodiversity decline, climate change, and pollution both within and outside the city (Grimm et al. 2008; Mcdonald et al. 2008; Pickett et al. 2008; Seto et al. 2012). Through their savaging resource consumption, waste generation and enormous greenhouse gas (GHG) emission, cities strongly influence ecological processes and biogeochemical cycles as well as alter regional and global climate and biodiversity. Cities and climate change feedback on each other in complex ways and together exert synergistic debilitating effects on ecosystems and biodiversity. However, cities can be instrumental in reducing climate change impacts and biodiversity loss, both locally and regionally. It is the target of the sustainable development goal (SDG) for cities (No. 11, *make cities and human settlements inclusive, safe , resilient and sustainable*) to reduce environmental impact of cities, provide universal access to green and public spaces for all, and preserve nature/environment networks in cities and their environs.

Among the many alternatives to conserve biodiversity, mitigate climate change and adapt to its impacts as well as address the multi-faceted challenges of cities are nature-based solutions (NbS): actions inspired by, supported by or copied from nature (European Commission 2015). Nature based solutions aim at enhancing sustainable urbanization, restoring degraded ecosystems, supporting climate change mitigation and adaptation, and improving risk management and resilience. They are energy and resource efficient, resilient to change, but must be adaptable to local conditions to be successful. They also offer multiple co-benefits for health, the economy, society and the environment (European Commission 2015). Green infrastructure/spaces, a classic form of NbS, have quite a long history in urban planning and in resolving urban environmental challenges (Benedict and McMahon 2002; Firehock 2010) although evidence of the effectiveness and implementation of NbS is still scanty.

A burgeoning wealth of literature exist on the functions and to some extent the processes underpinning the existence of urban nature but mainly from cities in the global north. In particular, the role of urban green spaces (UGS, or vegetation) in adapting to and partially mitigating climate change and its impacts (Jo and McPherson 2001; Jo 2002; Nowak and Crane 2002; Pouyat et al. 2006; Davies et al. 2011; Strohbach and Haase 2012; Edmondson et al. 2012; Edmondson et al. 2014) and averting biodiversity loss (Alvey 2006; Pickett et al. 2008) have been thoroughly examined. Biodiversity and nature conservation in cities can contribute to protecting the climate by avoiding emissions and capturing carbon in plants and soil and support adaptation to climate change (Natural Capital Germany-TEEB DE 2015). In recent years, emphasis on urban biodiversity studies have shifted from merely understanding the spatio-temporal dynamics and drivers of species richness/diversity patterns (Balmford et al. 2001; Araújo 2003; Hope et al. 2003; Kinzig et al. 2005; Faeth et al. 2011; Elmqvist et al. 2013) to establishing how modifications in species and trait states of urban species (Knapp et al. 2008a; Knapp et al. 2008b) affect ecosystem function. Meanwhile ecosystem services from UGS have been well elaborated (Bolunds and Hunhammer 1999; Tzoulas et al. 2007; Coutts and Hahn 2015).

Nevertheless, the global skewness and paucity of knowledge about NbS to urban environmental problems in the global south are well acknowledged (Aronson et al. 2014; Fischer et al. 2016). Since developing countries are still in the process of rapid urbanization, there are rife opportunities to construct cities with sufficient green cover, to protect sensitive ecological zones, and avoid or minimize environmental challenges confronting already established cities.

Africa, which is billed to become considerably more urbanized in the near future, is characterized by severe poverty (slums) (Chen and Ravallion 2007; Baker 2008), high vulnerability to climate change related hazards (heat waves, desertification, floods, droughts, diseases i.e. malaria), compounded by uncontrolled population growth and unplanned urban land expansion (Giugni et al. 2015). Consequently, dependence on urban nature for sustenance is high (Cilliers et al. 2013; Zérah and Landy 2013) and overexploitation of resources in the hinterlands is accelerating degradation and desertification. Some evidence that UGS (urban nature) can aid coping with and partially attenuate climate change impacts (Lindley et al. 2015) and biodiversity loss/modification (van Rensburg et al. 2009; Seto et al. 2012; Aronson et al. 2014) already exist. However, considering the wide socioeconomic, geopolitical, and ecogeographic disparities in African cities, more evidence is needed to set the context appropriately. The amount of ecosystem services and disservices from UGS can be linked to the biological diversity, extent (cover), composition and distribution of UGS, which in most African cities are fraught with uncertainties. These uncertainties impede adequate planning and management of UGS and undermines comprehension of biodiversity patterns and functional capacity of urban ecosystems in developing countries. The present study attempts to portray the relevance of incorporating nature/green spaces into cities in the global south in the light of biodiversity conservation and climate change mitigation and adaptation using remote sensing and ecosystem inventory techniques in Kumasi, Ghana. Green spaces are not just recreational spaces or aesthetic artefacts, but also important embodiments of biological diversity and several ecosystem services (ESS) such as carbon sinks.

1.2 Objectives

The goal of this study is to assess the extent, composition, distribution and function of green spaces in Kumasi, Ghana. The specific objectives included; to

1. map and examine the spatio-temporal dynamics of UGS at a citywide scale.
2. map the distribution and analyze the carbon storage potential of UGS at a citywide scale
3. analyze the impacts of urbanization on the diversity, co-existence and diversity-productivity relations of tree species in the UGS of Kumasi, Ghana.

1.3 Hypothesis

Cities support a wealth of plant diversity in UGS which can be sufficient to partially sequester some of the GHGs they emit and enhance environmental sustainability.

Premises

- The theoretical background of the study denotes that sufficiently providing for UGS in cities is an optimal and efficient means to sustainably supply ecosystem services to meet the wellbeing of urban inhabitants.
- It is assumed that urban areas support a variety of UGS types which in turn contain a wealth of plant diversity unique to the city in terms of species, trait, adaptability and function and which together diversify the ESS they deliver.
- Regions yet to undergo considerable urbanization, present the greatest opportunities to ensure nature is adequately integrated into the urban fabric, both morphologically and physiologically.
- Several scientific studies underscore the capability of cities to combat local climate change crisis, attenuate global biodiversity loss, and boost urban sustainability but the evidence is insufficient and regionally skewed.

The sub-hypothesis include:

1. The luxury effect hypothesis (Hope et al. 2003) – the distribution of vegetation or green cover within the city depends on the socioeconomic status of the suburbs (submetropolis).
2. Urban tree species/trait diversity and carbon sequestration depend on the UGS type and urban zone in the city.

1.4 Scope of the study

The urban landscape is a complex socio-ecological system in which the ecological subsystem is subdued by the social subsystem (processes and influence) in its morphological expression locally. In other words, urban landscapes are the most human dominated ecosystems on earth and occur at one extreme end of a continuum of ecosystems (prestine to urban): so arranged to depict the increasing degree of human influence (Collins et al. 2000; Grimm et al. 2000). Consequently, most solutions to urban environmental challenges are technically engineered and socially oriented. This study digresses from this worldview to embrace nature into the fabric of the city as a solution to urban environmental challenges. It is common knowledge that green spaces are synonymous to public parks, exploited for their recreational, health and scenic benefits. Here, the horizon is stretched to encompass private lots and cultural sites. The study assumes that UGS vary in extent, composition, distribution, and perform several functions. It further assumes that the species and trait diversities of the urban landscape are regionally unique and inherent in its socio-ecological origins. It is acknowledged that carbon storage in vegetation and soils in cities is 1) only a petite part of the measures of carbon mitigation in cities and 2) does not complete the carbon budget of the city.

1.5 The organization of the study

The organization of the thesis is as follows. The trends and consequences of urbanization in Africa with a special section on UGS management challenges and adaptation to climate change issues in Kumasi, Ghana are discussed in chapter 2. Chapter 3 addresses the dynamics of UGS in the study area: highlighting the spatial and temporal fates, possible distributional injustices and the composition of UGS in Kumasi. This is followed by a comprehensive analysis of vegetation and soil carbon stocks and carbon mapping in Kumasi, Ghana in chapter 4. Chapter 5 discusses tree diversity patterns among UGS types and urban zones in Kumasi: seeking to unearth the principles underlying species coexistence and ecosystem productivity at varying scales. Chapter 6 concludes and summarizes the findings of the study with special dedication to the outlook on future research. Reference section and the appendices are the final add-ons to the thesis.

2 GROWING URBANITIES, URBAN CLIMATE RESILIENCE AND URBAN GREEN SPACE MANAGEMENT IN AFRICA

2.1 Introduction

Besides rapid urbanization processes, cities in Africa are characterized by high informality and poverty, high vulnerability to climate related disasters, relatively high GHG emission rates, and low infrastructure, hence rife opportunities exist for African cities to develop effective adaptive measures to cope with climate change (Taylor and Peter 2014).

Mitigating and adapting to climate change entails reducing GHG emission rates. Three principles to aid the creation of a carbon-neutral future which can be adapted to cities include: 1) planning (at city and national level) for a low-carbon future, 2) developing policies that trigger changes in investment patterns, technology, and environmental behavior of urbanites, and 3) protecting the interest of the heavily affected urban poor (Fay et al. 2015).

An important action to mediate a carbon-neutral future and engender climate resilience in urban areas is improving carbon sinks (e.g. vegetation and soils; IPCC 2013). In cities in Africa, protecting, conserving, and managing green spaces within the city matrix and along sensitive ecological zones offer numerous ecosystem services including reduced flash floods and heatwave impacts, improved air quality, carbon sequestration, food security.

However, whether urbanization in Africa is an opportunity for or catastrophic to Africa's urban climate resilience remains nebulous. Thus, this chapter discusses 1) urban population and land expansion patterns in Africa in the light of climate change and 2) climate change adaptation, resilience, and green space management constraints in Kumasi, Ghana.

2.2 Methodology and approach

These objectives were pursued by, first, compiling and analyzing national urban population data for the entire Africa to put Africa's current urban population growth in context. Second, studies with a focus on urban land expansion using remote sensing were reviewed to provide insights on urban land dynamics on the continent. Cities were grouped into three based on their population size: mega (≥ 10 million), medium (1 - < 10 million) and small (<1 million) inhabitants. Total area of the city, change in built-up area, change in green space area, and duration of the study (or period during which change occurred) were extracted from these studies. Rates of growth in urban land area and per capita green space area for each city considered were calculated. The criteria for the selection of a city was based on the availability of published land cover/land use and population growth data. The UGS dynamics data were evaluated and complemented with literature reviews on urbanization impacts on climate change and the well-being of urbanites. Third, a resilience matrix was applied at an elicitation workshop involving academics from Ghana based at Center for Development Research (ZEF), University of Bonn, during which responses to how different UGS management may contribute to urban climate resilience in Kumasi, Ghana were obtained. Current adaptation strategies to climate change in Kumasi were also reviewed.

2.3 Urban population growth in Africa

About 54 % of the world's population now lives in urban areas, and all projections signal a world that will get more urban. Africa, which was without Western-styled cities at the onset of the 20th century, currently accounts for 12 % of the world's urban population. From 10 % in the 1950s, Africa's urban population amplified steadily to 40 % (439 million) today and is projected to reach 56 % (1.1 billion) by 2050. The numbers of megacities and medium-sized cities are expected to, respectively, double and quadruple by 2030 (United Nations 2014). Hosting 25 % of the world's fastest growing cities, behind only Asia with 50 %, Africa will become the fastest urbanizing continent between 2020 and 2050 (Satterthwaite 2007; United Nations 2014). Hence, Africa's urban population will constitute 21 % of the world's urban population by 2050.

2.3.1 Historical background

As early as 3200 B.C., large settlements already existed in Africa, initially confined to North Africa and later spreading to sub-Saharan Africa (SSA) (Özden and Enwere 2012). Ancient urban centers and peri-urban areas were characterized by their ability to produce agricultural surplus, specialized craftsmen, and monumental architecture (Coquery-Vidrovitch 2005). However, compared to contemporary urban centers, cities in ancient Africa were rare, low in population, small in size, and indigenous in character but nonetheless vibrant politically, economically, and socially.

Contact with Arab and later European merchants and missionaries fostered the rapid spread and development of cities (Kitto 2012). Colonization, economic expansion and international politics changed the face of African cities, introducing new technologies, and creating economic opportunities that stimulated the attractiveness of these cities. Indeed, the history, shape and character of most African cities today can be traced to colonial city plans, designs, function, and policies (Watson and Agbola 2013). For instance, urban plans for Lusaka, Zambia and Kumasi, Ghana were based on Howard's "Garden City" concept – the archetypical car-oriented elitist European city (Quagraine 2011; Watson and Agbola 2013). However, such colonial master plans did not anticipate the sprawl that has redefined the shape and configuration of modern African cities.

2.3.2 Current urbanization trends in Africa

Cairo, Egypt; Lagos, Nigeria; and Kinshasa, DR Congo are the only megacities (≥ ten million inhabitants) on the continent and contribute 15 % of the urban population. About 66 % of Africa's urban population lives in cities with 1–5 million people (UN-Habitat 2014). Of these, 16 cities are in West Africa (e.g. Kano, Dakar, Accra, Abidjan), nine in southern Africa (e.g. Johannesburg, Maputo, Harare and Lusaka), seven in each of North (e.g. Fes, Tripoli, Algiers, Rabat), East (e.g. Dar es Salaam, Nairobi, Addis Ababa, Antananarivo) and four in Central Africa (e.g. Doula, Yaoundé, Brazzaville, Mbuji). Small cities (< one million inhabitants) are generally regarded as the fastest growing cities in the world (2.4–6 % per annum) (United Nations 2014).

Although Africa remains the least urbanized continent, sub-regional variations are wide. Excluding Mozambique, Zambia and Zimbabwe, southern Africa is the most urbanized subregion with 61 % of the population living in urban areas, followed by North Africa with 51 %. In Central and West Africa the share is about 44 %, higher than in East Africa where it is 25 % (United Nations 2014).

Most of the urban population is concentrated in coastal areas (e.g. Gulf of Guinea), alluvial plains (e.g. Nile River) or lacustrine plains (e.g. Lake Victoria). Urbanisation is most rapid in West and East Africa, and this is expected to remain so in the coming decades. The urban population in these regions will rise to about 390 million and 328 million, respectively, by 2050 (Figure 2.1).

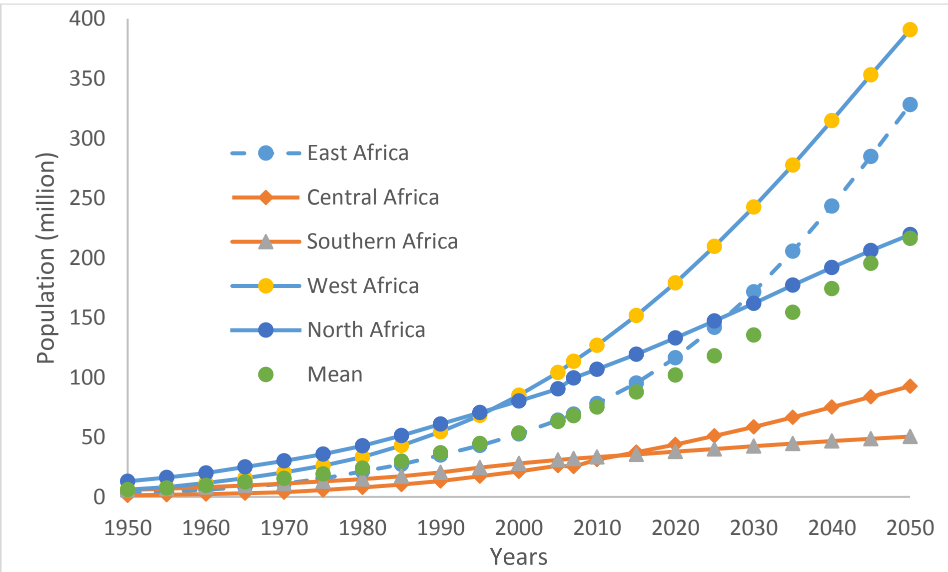


Figure 2.1Urban population growth in the African subregions (Data from the UN-Habitat database [UN-Habitat 2015**]).**

2.3.3 Causes of urban population growth

Urbanization in Africa has been attributed to rural-urban migration. Demand for labor during the primordial industrialization era propelled the exodus of the rural inhabitants into towns and cities (Caldwell 1969). Additionally, civil unrest and violence due to political instability, natural disasters provoked by climatic events (e.g. drought and flood-driven famine), excommunication of individuals from tribal life, and desire to taste urban life triggered rural-urban migration (Caldwell 1969; Satterthwaite 2007; Henderson 2014).

Natural increases through high birthrates and reclassification of rural areas as urban areas now provide the most noteworthy explanations of the current urbanization patterns in Africa (Kessides and Street 2006; Potts 2012). The availability of better health care systems in the cities has increased natality while reducing mortality rates. In resource-endowed countries like Ghana, Ivory Coast or Nigeria, proceeds from the export of natural resources are disproportionately invested in developing urban goods and services, which further spurs urbanization (Jedwab 2012).

However, due to lack of opportunities in the cities, high living costs and cultural discomfort of migrants, rural-urban migration is plummeting (Beauchemin 2011; Potts 2012). In Burkina Faso and Ivory Coast, for instance, counter-urbanization processes have been detected (Beauchemin 2011). Nevertheless, inter and intra city mobility among urbanites remains widespread (Simone 2011). The question is how will urbanization in Africa influence urban life economically, socially, culturally, and environmentally?

2.3.4 Side effects of urbanization: poverty and cultural erosion

The number of urban poor (income below USD 2.15 per day) is rising even faster than the global urban population (Chen and Ravallion 2007). About 72 % of Africa's urban population lives in slums and represents the most prevalent and fastest growing group of poor people in the world. About 40 % of Africa's urban population currently live below the poverty line (<USD 1.08 per day) and will likely remain so by 2050 (Chen and Ravallion 2007; Baker 2008). As a consequence, Africa's urbanization is characterized by inadequate asset base (e.g. infrastructure), unavailability and uneven access to services, amenities, education and human capital development, and worsening environmental conditions (Satterthwaite 2001; Kessides and Street 2006; Baker 2008). Thus, African cities are not the engines of economic growth, characteristic of cities on other continents, but instead are a cause and a major symptom of economic crises (World Bank 2000). This situation arises out of scarcity in development opportunities and high proportion of unskilled labor. Interestingly, most cities are primarily centers of administrative and political power, and require skilled manpower.

Although not thoroughly researched, the majority of Africa's urban poor seemingly live in East, Central, and West Africa (Mabogunje 2005). Country-level studies indicate that 25 % of the households and 30 % of the population in Mombasa, Kenya live below the absolute poverty line of <USD 2.15 per day (Rakodi et al. 2000); 50 % of the population of Maputo, Mozambique is poor, with 30 % characterized as destitute (Jenkins 2000); 95 % in Kinshasa, DR Congo have low incomes, and 90 % are jobless (Mia et al. 2014).

The westernization of African cities exerts strong impacts on cultural values. For instance, the large extended family system and communal life are giving way to a nuclear family system, individualism, and an unhealthy scramble for survival as inter-tribal wars increase in poor urban neighborhoods. An example is Mombasa, Kenya, where frequent clashes occur between coastal residents and up-country immigrants due to economic inequality fueled by a political system that is tribally inclined (Rakodi et al. 2000). Technology and mechanization have replaced the manual and animal traction culture typical of the region. Organic waste, formerly an important asset as fertilizer, has become adulterated with non-biodegradable material and a health menace in the cities.

These factors notwithstanding, the traditional music and dance culture as well as other pleasant aspects of the African heritage continue to thrive in cities.

2.3.5 Urbanization impacts on quality of life and health

The high resource consumption in urban areas coupled with the transformation of nature has triggered the emergence of Urban Heat Island (UHI) effects common in industrialized cities. This effect refers to the surface temperature differences between urban and suburban (or rural) areas (Peng et al. 2012), and is attributable to numerous factors. These include urban land-use and cover patterns, population size, increase in impervious area (low albedo, high heat capacity), decrease in area covered by vegetation and water evaporation (decline in evaporative cooling), increased surface area for absorption of solar radiation due to multi-story buildings, canyon-like heat trapping structure of high-rise buildings (Grimm et al. 2008), and the broadening long-wave radiation trap of CO_2 in the atmosphere. A recent evaluation of UHI effects in cities worldwide, including 47 in Africa, revealed differences in day and night temperatures between urban and suburban areas of 1.5°C and 1.1°C, respectively (Peng et al. 2012). In Sekondi-Takoradi, Ghana, urban development resulted in 4.3°C in temperature within 17 years (Kumi-Boateng et al. 2015).

Furthermore, sudden heat waves claim numerous lives every year in many cities in Europe and North America (Gabriel and Endlicher 2011; Walters and Lane 2014). Rising air pollutant concentrations in cities interact with climate change and UHI leading to health burdens on cities (Harlan and Ruddell 2011). Outdoor air pollution in African cities accounts for 49,000 premature deaths annually (UN-Habitat 2008). In Durban, South Africa, an inventory of GHGs emitted from the transport sector revealed high concentrations of particulate matter (PM_{10}), NO_x, CO and SO_2 (Thambiran and Diab 2010). In China, reducing pollution in Beijing during the 2010 Olympics led to a 23-g weight gain in newborn babies compared to their counterparts born during similar time periods in previous years (Rich et al. 2015). Indoor air pollution causes between 2.7 and

2.8 million premature deaths globally, and is the leading cause of respiratory ailments among women and children in African slums (UN-Habitat 2008). A clear policy goal in Africa's urbanization is required to design and construct decarbonized cities with improved indoor and outdoor air quality.

Other climate change-related vulnerabilities include the prevalence of waterborne diseases such as cholera, malaria, dengue and yellow fever (Unger and Riley 2007; WHO 2009), and exacerbated droughts and floods (IPCC 2007). Over 90 % of the victims of these precipitation-related disasters are the poor living in informal settlements and slums (ActionAid 2006; Amoako and Boamah 2014).

2.4 Environmental impacts of urbanization

2.4.1 Urban land expansion and land-use change

Globally, urban areas occupy about 3-4 % of the earth surface and are growing at a rate twice that of the global population (Angel 2011; Seto et al. 2011). With 256 cities and a population of 132 million, urban areas in SSA occupy an area of approximately 13,000 km^2 while those in North Africa with 115 cities and a population of 53 million occupy an area of 5,342 km^2 (Angel 2011). These areas combined are predicted to increase by 590 % by 2030 (Seto et al. 2011).

Urban expansion occurs unevenly, mostly concentrated along the Guinea coast of West Africa, the Nile River in Egypt, the northern shore of Lake Victoria in Kenya and Uganda stretching into Burundi and Rwanda, the Kano region in northern Nigeria, and greater Addis Ababa in Ethiopia (Seto et. al. 2012). Losses in natural land cover to urbanization are greatest in East, North, and West Africa and slowest in southern and Central Africa (Nguh 2013; Sebego and Gwebu 2013; Otunga et al. 2014).

Generally, the mega and medium-sized cities are undergoing the most rapid land expansion with significantly higher expansion rates of 743 and 620 ha/year, respectively (Table 2.1). However, small cities with < 1 million inhabitants are numerous and, therefore, growing fast in terms of their share of the total population (United Nations

2014; UN-Habitat 2014), and with an average land expansion rate of 129 ha/year, this should be cause for concern.

While many underlying factors influence urban land expansion, in Africa it is primarily driven by population growth. In most cities in Africa, direct correlations exist between population growth and increase in urban land area (Wu et al. 2003; Matthieu 2008; Seto et al. 2012; Sylla et al. 2012).

Table 2.1: Changes in mean urban land-use characteristics in mega, medium-sized and small cities in Africa. Numbers in parenthesis are percentage change in area.

City type	Average population (million)	Average city area (ha)	Average period of change (years)	Average change in built-up area (ha)	Average change in green space area (ha)	Average green space area (%)	Rate of urban expansion (ha/year)	Green space per 1000 inhabitants (ha)
Mega	19.20	97,227	23	17,000 (93.3%)	-16,500 (46%)	42	743	0.47
Medium -sized	2.70	84,406	21	13,500 (199.4%)	-12,000 (22%)	39	620	12
Small	0.52	21,432	24	2,215 (148%)	-2,212 (21%)	57	129	23

Compiled from: Adepoju 2006; Aduah and Baffoe 2013; Ayila et al. 2014; Diallo and Bao 2010; Fanan et al. 2010; Forkuor and Cofie 2011; Hassan 2011; Kamusoko et al. 2013; Mohammed et al. 2015; Mundia and Aniya 2005; Nguh 2013; Otunga et al. 2014; Sebego and Gwebu 2013; Fanan et al. 2011; Vermeiren et al. 2012; Wafula and Gichuho 2013; Weber and Puissant 2003; Wu et al. 2003; Al-sharif et al. 2013; Sahalu 2014.

Horizontal expansion of cities encroaches upon environmentally sensitive zones such as wetlands, protected nature areas, agricultural land and open parklands, causing a decline in vegetation cover and primary production (Ramankutty et al. 2010). Cities in SSA have always experienced a growth in built-up areas at the expense of agricultural and forest lands causing about 12–77 % loss in tree cover and 18–50 % loss in farmlands within an average period of 22 years (Aduah and Baffoe 2013; Fanan et al. 2011; Forkuor and Cofie 2011; Mundia and Aniya 2005). In most cases, agricultural and rangelands are the most severely converted, although non-forest areas in Bamako, Mali increased within a 20-year period due to interland use conversions (Diallo and Bao 2010).

Vegetation loss due to urban land expansion augments and exacerbates climate change and its impacts. By replacing trees with grey infrastructure, the carbon (C) stocks in the vegetation and soils are released to the atmosphere via several processes. At an annual built-up area expansion rate of 340 ha, SSA cities could be emitting about 68,000 t C per year due to urbanization-driven forest loss. It is estimated that urban expansion-related deforestation in Africa will emit about 490 million t C by 2030 (Seto et al. 2012). Land-use conversion and their ancillary effects of accumulated CO_2 concentrations in the atmosphere tinker with climate variables, altering precipitation and temperature patterns at local and regional scales. However, urbanization-driven vegetation loss and its effects on GHG emissions and climate change require further investigation given the wide ecological and socioeconomic disparities among African cities.

A slightly divergent view posits that land-use change rather than climate change may have more acute deleterious thermal effects on urban living. A temperature simulation study in Addis Ababa, Ethiopia and Dar es Salaam, Tanzania reveals converting vegetation to a built-up or bare area may lead to small-scale instant 25°C rises in temperature compared to climate change-related larger-scale temperature increases of 1 – 2 °C which require several decades to occur (Lindley et al. 2015). Also, the hard, compacted surfaces characteristic of cities redefine water flow paths within the landscape, impeding infiltration and facilitating overland flow, which together with elevated water tables cause frequent flash floods and major flood events (Stephan Pauleit and Duhme 2000) .

However, urbanisation does not necessarily always exacerbate loss of vegetation (Pouyat et al. 2006). In arid areas, the environmental conditions of cities resulting from elevated CO_2 emissions, soil nutrient improvements from wastewater irrigation and organic waste disposal, and higher temperatures can provide better conditions for plant growth and hence induce city greening.

2.4.2 Resource consumption and greenhouse gas (GHG) emissions

A standardized measure of human resource consumption is the Ecological Footprint (EF). This is a measure of how much biologically productive land actually sustains a given population of people indefinitely regardless of its location (Rees and Wackernagel 1996). The EF of cities varies depending on the level of industrial activity. In Africa, EF and related bio-capacities (an estimate of a system's biological productive and waste absorption capacities) of cities are 1.1 global hectares (gha) and 1.4 gha, respectively, which is well below the global average EF of 2.7 gha and biocapacity of 1.8 gha (GFN, 2010). The lower EF compared to biocapacity values mean that African cities are consuming within the ecosystem productive capacity and can naturally regenerate. In other words urban resource demand is sparingly below supply (Wackernagel et al. 2006; Rees and Wackernagel 1996).

By being the predominant source of energy for the African urban population, particularly the poor, fuelwood and charcoal constitute a major part of the EF of cities (Razack et al. 2013). About 60 % of African urban households depend on fuelwood for cooking (AREAP 2011). The fuelwood is obtained from forests in peri-urban and neighboring hinterlands. In Dar es Salaam, Tanzania, the radius of exploitation areas in the surrounding forests for timber and charcoal expands at a rate of 9 km/year and 2 km/year, respectively, and causes a reduction in C storage and species richness up to a radius of 220 km from the city center (Ahrends et al. 2010). Urbanization in Africa is therefore expected to further exacerbate deforestation in the hinterlands, and weaken the potential for terrestrial C sequestration and consequently negatively affect the temperature, relative humidity and precipitation patterns. As urban population and demand for resources sour in Africa, city EF may soon overshoot bio-capacity, consequently resulting in unheralded environmental challenges including exacerbated GHG emissions.

2.4.3 Addressing climate change: Mitigation and adaptation opportunities

If managed properly, cities may be both a vice and virtue from a climate change perspective. By taking advantage of the huge human capital concentrations, cities can innovatively contribute to mitigating emissions, and provide measures of adaptation and resilience to climate change (Fong et al. 2014; N. B. Grimm et al. 2008).

In climate change parlance, adaptation refers to proactive adjustments in natural or human systems in response to actual or expected climatic stimuli, their effects or impacts, whereas mitigation comprises reactive anthropogenic interventions to reduce the sources or enhance the sinks of GHGs (IPCC 2001). Ultimately, both aim at minimizing the undesireable effects of climate change, and therefore an effective response should explore the two simultaneously (Parker-Flynn 2014).

Adaptation strategies are best linked to life style and policy choices. In the context of climate change in African cities these include: avoiding human habitations in flood-prone areas (includes relocation etc.), building high walls around houses, constructing drains and channels to redirect flood water, maintaining adequate tree cover for shade, cooling, filtering air pollutants and enhancing subsurface runoff, and constructing well-ventilated housing to improve the indoor microclimate and minimize waterborne diseases and indoor pollution.

Mitigative strategies include reducing travel distances within cities, promoting public transport systems (i.e. fewer cars on the roads), and improving fuel-use efficiency of vehicles (Stockholm Environment Institute 2013). Fitting vehicles with air pollution filters, increasing the number of diesel-powered vehicles and decreasing that of petrol-powered vehicles, and the use of diesel particulate filters are among other alternative measures that could reduce emission and pollution levels in African cities (Kennedy et al. 2010). Maintaining dense and compact cities (Kennedy et al. 2010; Makido et al. 2012), and the culture of hiking and cycling in cities (Thambiran and Diab 2010) could minimize transport emissions. Using alternative sources of energy and implementing improved waste management approaches are also options to reduce emissions and subsequently impacts on climate change and the wellbeing of urbanites. Sequestration of carbon in urban trees, soil (Nowak and Crane 2002; Pouyat et al. 2006; Davies et al. 2011; Strohbach and Haase 2012), landfills, buildings/furniture and in people (Churkina et al. 2010). However, the majority of these adaptation and mitigation measures, while promising, lack empirical backing, and should be the bases for future research.

2.5 Green space management and adaptation to climate change in Kumasi

2.5.1 Background

Kumasi metropolis is the second largest and fastest growing city in Ghana with a land area of 254 km^2 inhabited by approximately 2.5 million people. The population density is about 8,000 persons per km^2 with an annual growth rate of 4.8 % (Ghana Statistical Service 2012; KMA 2013). Not only is Kumasi a central point for transiting travelers from within and beyond the borders of the country, the largest open market in West Africa is also located here, thus making the city an economic hub (Adarkwa 2011).

Urban Kumasi in the early 19th century had a population of about 1,500 concentrated on a land area of about 2 km^2 (Amoako and Korboe 2011). Its growth and development took place after the Asante Kingdom was defeated by the Britains in the late 19th century who subsequently developed a Western infrastructure in the town. The establishment of a railway system opened Kumasi to merchants from the coastal belt while brisk trade, cocoa boom, and establishment of offices fostered new and refined infrastructural development beyond the town’s boundary. By 1950, Kumasi's land area had expanded to 25 km^2, and has since swelled to its present size and population (Figure 2.2 and 3.1).

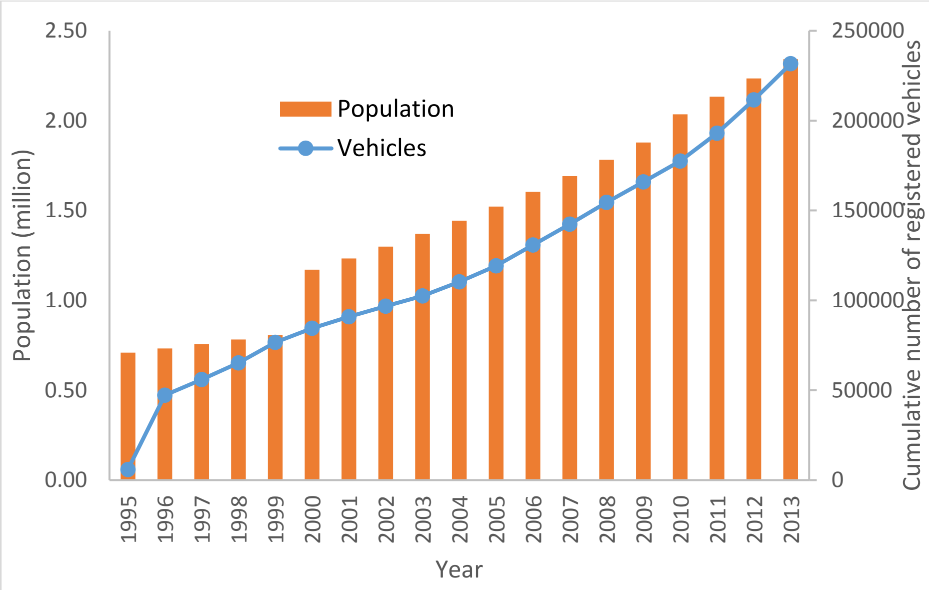


Figure 2.2 Population and cumulative number of registered cars in Kumasi metropolis, Ghana, since 1995 Data source:(DVLA 2014).

2.5.2 Climate change and adaptation

The explosion in population led to major land use transformations. Consequently, Kumasi, once dubbed "Garden City" of West Africa because of its lush vegetation cover (90 % in the 1970s and earlier), has witnessed its green cover decline over the years to about 50 % (Quagraine 2011; Campion 2012) mainly due to conversions to build-up and other grey infrastructure. It is worthy to note that biomass energy supplies 64 % of the total energy consumed in Ghana (FAO 2009) and the continues massive dependence on fuelwood for cooking in Ghanaian cities (Ghana Statistical Service 2012), will further exacerbate deforestation in the hinterlands and CO_2 emissions. Already, due to progressive hikes in vehicular usage (Figure 2.2), Kumasi's transport sector GHG emissions (97.6% of which is CO_2) increased from 665,000 to 860,000 t at a rate of 39, 000 t/year between 2000 and 2005 (Agyemang-Bonsu et al. 2010). Combinded with the large piles of waste generated, demonstrates Kumasi's high potential as a source of GHGs relative to other cities in this region.

Apparently the urbanization processes have resulted in climatic changes in Kumasi. An increase of at least 1°C in daily minimum and maximum temperatures between 1970 and 2000 (Manu et al. 2006), and a 20 % decline in precipitation over the past 40 - 50 years (Owusu 2009) have been reported. In the last 10–15 years flood frequency and intensity in the city ascended, imputed mainly to poor urban planning and ineffective protection efforts for wetlands and riparian ecosystems (Campion and Venzke 2011; Campion 2012), but cannot be entirely disentangled from climate change. In coping with these floods and other hazards, residents in low lands and flood prone areas of Kumasi resort to constructing embankments around houses, raised walkways in house compounds, stilt foundations for houses, relocate till water subsides or permanently away from the community, keeping belongings in higher grounds (e.g. roof tops, tables, etc), dredging and channel construction, and having strong faith in the divinity (Campion 2012).

Judicious integration of green spaces into the landscapes of cities can be instrumental in adapting to and coping with climate change. Evidence of availability of green spaces in Kumasi (see Chapter 3) suggests that the residents enjoy the evaporative cooling, shade and air cleansing benefits from these spaces. By setting aside, flood-prone areas and lowlands as UGS maintained and managed purposely for recreation and biodiversity conservation, floods can be avoided and the cost of flood damage and water-related diseases minimized. Overall, adaptation interventions should encompass three key aspects: infrastructure, community-based, and institutional adaptations (Lwasa 2010). Adequately and evenly integrating UGS into the city matrix is crucial in effectively harnessing their complete positive impacts. The use of green spaces offers an added advantage of climate change mitigation (see chapter 4). Management issues related to enhancing climate change resilience through green spaces are discussed next.

2.5.3 Green space management issues and urban resilience

For implementing greening actions, community participation is fundamental, and a general consensus is crucial for operationalization. In developed countries, top-down mechanisms where governments and local authorities plan, decide and invest in promoting urban greening seem to be hegemonic, while in developing countries the situation appears to be determined by bottom-up processes. Hence, policy instruments that affect the social and environmental performance are key.

In this context, the resilience premise was applied to identify factors that favour or negatively influence the existence and maintenance of UGS (Carpenter et al. 2001). This implies that increasing the city's resilience to climate change requires increasing the populations' adaptation and mitigation capabilities as described above. Resilience is the ability of a system to absorb and reorganize itself to overcome shocks and changes in its surroundings (Walker et al. 2003). Resilience may include societal and ecological subsystems in mutual interaction (Gallopin 2006), and it is circumstance- and time-dependent relying on constant adjustments in the system to fit with the external changes, thus leading to adaptive processes (Smit and Wandel 2006).

The performance and potential of each UGS to contribute to the city's resilience to climate change were assessed against the following contrasting criteria: 1) the encouraging decisions and actions that promote UGS, and 2) the pervasive decisions and actions that deplete UGS. In both cases, three components were taken into account: 1) the managerial actions (what?), 2) the actors or persons responsible (who?), and 3) the underlying reasons (why?). Responses and their tabulation were carried out in an elicitation workshop involving Ghanaian academics based at ZEF and the author, and complemented by first-hand information gathered from stakeholders in the field and secondary data from literature (Table 2.2).

Table 2.2 Managerial actions/decisions, actors and underlying reasons that favour and weaken UGS existence and maintenance in Kumasi, Ghana (see appendix 4 for detailed description).

Urban green space (UGS)	Favouring UGS	Weakening UGS
Plantation & Natural Forest	**What?** Planting trees, Conserving naturally established trees **Who?** Private landowners, administrators of public institutions, chiefs **Why?** Aesthetics, shade, firewood, enhances social interaction, mitigates climate change, regulates biogeochemical cycles, carbon sinks	**What?** Tree felling, tree cutting **Who?** Fuelwood gatherers, land developers, chiefs, local government (KMA[1]), town and country planning) **Why?** Impediments to 'development', expansion in urban land, damage to public infrastructure (building foundations, electricity/telephone cables), public health and safety (habitats for dangerous animals, hubs for crime planning), need for fuelwood
Home garden	**What?** Food/fruit crop cultivation, lawns **Who?** Private residential heads, tenants in gov't residential areas **Why?** Food security, augments household income, medicines; beautification, pleasure, improved air quality; inherited practice, shade, love of vegetation, provision of environmental services	**What?** Housing without home gardens **Who?** Owner **Why?** Fear of hazards like snakes; invasion by criminals, intruders; destruction of buildings/walls through roots and branches; cultural reasons; urbanisation (converting gardens into more profitable structures)
Institutional compounds	**What?** Tree plantings **Who?** Heads/activists in institutions/public offices **Why?** Shade, fruits; beautification; windbreaks, erosion checks, boundaries; influence of management interest & background	**What?** Bare compounds, land-use change **Who?** Institutional authorities/heads **Why?** Public hazard, destroy buildings, habitats for dangerous animals, hideouts for criminals, fallen branches; generate waste, litter; lack of management know-how and tools; allocation to other uses, e.g. building construction
Farmlands	**What?** Cultivation of marginal lands **Who?** Tenant farmers, (unskilled) urban dwellers, laborers **Why?** Food production; income generation Pleasure	**What?** Uncultivated fields, use of black waters **Who?** City authorities, land owners **Why?** High demand for land; urbanisation (land-use change); flood prone, pollution source (fertilizers & pesticides)
Cemeteries	**What?** Tree cultivation, tree maintenance **Who?** Traditional heads (chiefs), local/city authorities **Why?** Revere the dead, respect, traditional/cultural beliefs; fear of the spirits; beautification, shade	**What**? Bare cemeteries, logging **Who?** Traditional heads (chiefs), local/city authorities, tree thieves **Why?** Create space for more burial grounds; clear encroachment; demand for land
Street trees	**What?** Plan(t) rows of trees along streets **Who?** City authorities, local stakeholders, individuals **Why?** Beautification; provide shade and cool areas (private use also);improve visibility and reduce accidents	**What?** Bare streets, logging trees, no or poor maintenance **Who?** City authorities (government), individuals **Why?** Interfere with electricity cables; smooth road passage; reduce hazards, e.g. falling branches, protruding stems, etc.; change of land uses, e.g. into shops
Public parks	**What?** Plant trees and grasses **Who?** Government, city authorities, investors **Why?** Shade, recreation, entertainment, public health; beautification; tourism, conservation of genetic resources	**What?** Land-use change **Who?** City authorities, investors **Why?** Poor foresight; high maintenance costs; more profitable alternative use (business opportunities); neglect
Grass/Range lands	**What?** Marginal lands **Who?** Private land owners, city authorities (KMA): **Why?** Flood mitigation; grazing; biodiversity conservation	**What?** Conversion of grasslands **Who?** Private owners, city authorities **Why?** More profitable alternative use; better alternative land uses; urbanisation (pressure for land-use change)

[1]KMA = Kumasi metropolitan assembly

In Kumasi, the measures that favour or disfavour UGS existence are a blend of top-down and bottom-up mechanisms. Several UGS are maintained by various interest groups for varied purposes. At the same time, these interest groups may convert the UGS to other preferred uses driven by socio-economic, cultural and political influences.

The relevant actors in UGS management are city authorities, private owners, 'chiefs' and to a limited extent non-governmental and community-based organizations (NGOs and CBOs). In the case of the city authorities, their competences and roles are regulated by local and national legislation and conventional property rights. These regulations, defined in the state-of-the-art of policy documents, although comprehensively and theoretically well framed, are mostly not applied.

The authority of the local and central governments over land is limited and lacks enforcing capabilities. Hence, the scope of influence in defining and administering UGS is frequently restricted to jurisdiction regarding, for example, public parks (i.e. botanic gardens, zoos, protected areas), and vegetation on institutional compounds.

Moreover, it is quite frequently observed that a site originally designated as UGS is in practice utilized differently or at best converted into grey infrastructure, not only by individuals with an interest in its benefits but also by public authorities who spot potential selfish benefits. This is not new. Kumasi has experienced several city plans since its foundation. The 1945 plan, conceived as a quintessential 'Garden City' plan according to Howard's concept, advocated for the creation of a 300 m green belt along stream channels and the establishment of urban parks within Kumasi but not on its periphery. Most of the designated green belt zone is currently occupied by grey/brown infrastructure, i.e. buildings, roads, and other land uses detrimental to UGS (Schmidt 2005). Adjustments as a result of population growth by re-designating land uses, mostly unplanned sprawl, has rendered these early plans immaterial. Kumasi's UGS may have declined drastically but its tag as a "Garden City" is still widely eulogized by its inhabitants.

Singular is the role of 'chiefs', a specific case in the region. With the exception of small areas of state land, all land in the Asante region is held in trust for the Asante people by their king, the *Asantehene*. He allocates land through a network of local chiefs and in conjunction with the office of the administrator of stool lands (*land held in allodial, (i.e. land ownership that is outright and absolute) title by a traditional head on behalf of a community or group of people*) (Devas and Korboe 2000). These rights are acknowledged by society and recognized by local and central governments.

However, some chiefs and their people regard UGS as wasteland, hence their protection can be contentious. Even recognized public parks and gardens and also sensitive wetlands that require mandatory protection may be annihilated if land values appreciate and the demand is high. The policy of non-interference in the chieftaincy issues by the government weakens its ability to promote and enhance development of UGS. On the other hand, the power of traditional authorities could be harnessed for the purpose of UGS conservation, environmental protection, and climate change mitigation/adaptation. Citizens swear allegiance to their chiefs, thus urban environmental policies instituted and administered through the chiefs can promote a green, climate change-resilient city. The involvement of chiefs in environmental management in the country is only now gaining momentum in cities and in the country.

Although potentially regulated by national and mainly local institutions, the management of UGS tends *de facto* to be the responsibility of private land users. Hence, individual behavior still appears to be the major determinant of both favorable and unfavorable decisions to green the city (Table 2.2). Individual behavior is at least unpredictable, but a pattern can be observed where decisions of land users are practical and obey only short-term interests. For instance, a good number of tree owning residents in Kumasi acknowledged the direct benefits, e.g. shading, air purification, food, etc., derived from UGS, but stated categorically that they would transform these spaces and erect more profitable structures such as buildings and shops once the need arose. Several household heads resent trees and green spaces in their compounds for the potential hazards they might pose. Among other disincentives, trees and green spaces regularly interfere with the roofs and foundations of buildings, litter and soil the compounds, increase fuel loadings and thus the risk of fires, provide habitats to dangerous animals such as snakes, scorpions, etc., increase the risk of damage due to falling branches, and may serve as hideouts for criminals. Yet there were others who for lack of space merely wished they had green spaces in their compounds. In general, the reasons favouring the establishment and maintenance of UGS include: 1) beautification, independent of socioeconomic status, property stand of the UGS, and authority position, 2) provision of goods, such as food, fodder, fuelwood, etc. (tangible benefits), and 3) provision of services, e.g. air quality improvement, shade, windbreaks, erosion checks, flood mitigation, etc. (intangible benefits) (Table 2.2). On the other hand, UGS existence is threatened by: 1) land-use conversion towards a more profitable use, e.g. houses, public buildings, roads, channels, etc., and 2) neglect of landscape plans, and *ad-hoc* legislation, and 3) urbanites' lack of awareness of the value of existing UGS.

As frequently observed in the Global South, the management of UGS lacks appropriate legislation, planning and/or enforcing capabilities. Consequently, their importance may be downplayed in favor of more profitable short-term interests and activities. Although this situation is often justified by the lack of financial means, it seems related to systemic malfunctions, such as inadequate governance expressed in the defiance of laws and in corruption.

At the individual level, decisions concerning management and promotion of UGS can generate a considerable impact in either a positive or negative way. Decisions appear influenced by a person's background (connection with nature, countryside provenance) and education, i.e. degree of information on the importance and roles of UGS, and finally by short-term interests. Although not thoroughly examined, it appears that people who live near the outskirts of the city are more likely to have vegetation in their compounds than those who live in the center of the city. People living on the outskirts, belong to the relatively wealthy class, most of whom are well educated and appreciate and conserve nature. Often though, the permanence of such UGS, mainly home gardens, cannot be guaranteed as they are mostly only temporary, awaiting conversion into some more rewarding permanent infrastructures when the economy becomes favorable.

2.6 Conclusion

Considering the growing awareness of urbanisation and the relevance of urban resilience to climate change impacts, understanding that urban resilience is multidimensional and accomplished via various means is crucial. Attaining climate resilience in cities is not a homogenous process and the significance of green spaces as part of resilience in cities must not be peripheral.

This chapter discussed the growing urban population in Africa in the light of climate change and the role of green spaces, and presents Kumasi as a case study to illustrate the potential of African cities to be climate resilient. Unequivocally, urbanization drives the depletion of natural land cover, exacerbates anthropogenic environmental change, and threatens human wellbeing on the African continent.

However, through improved management of the urban space and environmentally friendlier life style choices, it is possible to cope with climate change and engender climate-resilient urbanization on the continent. Adequate management of green spaces in African cities could minimize air pollution and lessen climate-related hazards such as heat waves, floods, droughts, and thus increase their resilience to climate change (Lindley et al. 2015).

The inadequate implementation of existing legislation and lack of *ad-hoc* policies leaves the green space management initiative to customary and private interests. Therefore, de facto bottom-up processes determine the existence and management of UGS. Here, the roles of chieftancy (traditional leadership) and individual landowners are particularly relevant.

Involvement of the government, traditional leaders and civil society in defining priorities, streamlining actions and enforcing them are essential requisites to sustain and enhance green cover in African cities. Empirical research to identify and operationalize measurements to confront climate change as revealed in this chapter are key, but without the appropriate governance maybe in vain.

3 URBAN GREEN SPACE DYNAMICS AND SOCIO-ENVIRONMENTAL (IN-) JUSTICE IN KUMASI, GHANA

3.1 Introduction

About 54 % of the world's population now lives in cities and is expected to rise to 66 % by 2050 (United Nations 2014), underlining the importance of cities on earth. Africa, presently predominantly rural but among the fastest urbanizing regions in the world, could have 56 % of its population in cities by 2050 (United Nations 2014). Besides causing severe losses in natural ecosystems (Seto, Güneralp, and Hutyra 2012), about 90 % of Africa's cities are prone to at least one environmental hazard (Di Ruocco, Gasparini, and Weets 2015), and two out of every five urbanites live in penury (Chen and Ravallion 2007; Baker 2008). UGS provide a variety of ecosystem services (ESS) and have the potential to enhance sustainability and resilience to environmental disasters as well as minimize poverty (Andersson 2006; Sandström 2009; Haq 2011; Benedict and McMahon 2002). Urban green spaces are diverse in character, composition and function and are often defined to include parks, street trees, urban farmlands, residential lawns and any open undeveloped/non-bare land within and immediately around cities (Benedict and McMahon 2002; Breuste et al. 2013).

The ESS provided by UGS are essential to maintaining ecological sanctity of cities, urban health and food security needs of the urban populace. For instance, home gardens and farmlands are essential sources of food, income and employment to the informal sector (Aworinde et al. 2013; Galhena, Freed, and Maredia 2013; Cilliers et al. 2013; Zérah and Landy 2013). UGS are also essential for improving air quality (David J. Nowak, Crane, and Stevens 2006; Jim and Chen 2008), shade provisioning (Bowler et al. 2010; Norton et al. 2015), noise reduction, water infiltration and purification (Stephan Pauleit and Duhme 2000; Bolund and Hunhammer 1999), for recreation and human health, particularly stress reduction and physical exercises (Thompson 2002; Tzoulas et al. 2007; Coutts and Hahn 2015), energy conservation, and a host of other ecological, social, cultural and psychological benefits. To emphasize their relevance, the SDGs advocate for the provision and universal access to urban green spaces by all urbanites by 2030 (United Nations 2015).

However, UGS extent and distribution vary among and within cities. On average percent verdant cover in medium (1 - 10 million inhabitants) and small (<1 million inhabitants) cities in Africa is 39 and 57, respectively (Chapter 2). The inter-city non-built-up cover ranges from 3.3 % in Omdurman, Sudan (Mohammed et al. 2015) to about 90 % in Nairobi, Kenya (Mundia and Aniya 2005). The extent and persistence of UGS depends on the city size and form, socio-political factors, population growth, economics, and biophysical factors (Fuller and Gaston 2009). Furthermore, in Africa UGS extent within cities are ill-defined and hardly planned for, and where they are planned for, the focus is solely on public parks and gardens (Mensah 2014a; Mensah 2014c; Quagraine 2011) leading to discordant characterization of the extent and composition of green cover among spatial scientists and urban planners. Coupled with institutional failures and path dependency, poor attitude towards public property, neglect and misconceptions about urban nature, conventional UGS cover often drastically decline in extent and condition (Mensah 2014b; Mensah 2014c). Within many African cities, UGS extent is inversely related to population increase (Tontoh 2011; Wu, Courel, and Rhun 2003; Kayembe wa Kayembe, Matthieu, and Wolff 2012; Sylla et al. 2012; Sebego and Gwebu 2013), hence future urban population growth would further deplete UGS cover in African cities, if UGS are not innovatively planned for and regularly monitored.

In addition, UGS within cities are not justly distributed. Availability and access are stratified based on socio-economic conditions of urbanites, race, and other socio-political and geographic factors (McConnachie and Shackleton 2010; Heynen, Perkins, and Roy 2006; Kabisch and Haase 2014; Stow et al. 2012). Uneven access to UGS is regarded an environmental injustice (Jennings, Gaither, and Gragg 2012; Wolch, Byrne, and Newell 2014). Most analyses focus on access to public spaces. As the urban poor in the developing world rely heavily on natural resources (Vollmer and Grêt-Regamey 2013; Cilliers et al. 2013; Zérah and Landy 2013) inequity in UGS availability and access has potential livelihood setbacks.

It has been suggested that discussions on urban nature inequity should encompass UGS other than public parks (Jennings, Gaither, and Gragg 2012) whereas incomplete understanding of what constitutes UGS can stifle its management and inclusion in planning programs (Matthews, Lo, and Byrne 2015). Moreover, to successfully plan for nature in cities, it is important to know the extent, composition, distribution and its functional characteristics (Niemelä 1999).

Medium resolution satellite images provide accurate and reliable means to map, analyze spatial patterns and temporal changes in land use/cover in urban landscapes (Herold et al. 2003; Van de Voorde et al. 2010). Prior studies have analyzed and mapped urban growth and processes in major African cities using high and medium resolution satellite imagery in the context of land use change and urban planning/expansion (Mundia and Aniya 2005; Mohammed et al. 2015), urban vegetation distribution in relation to wealth (Stow et al. 2012) and a host of others. By combining spatial and equity measurement techniques, it is possible to analyze drivers and distributional inequities associated with urban vegetation cover.

The goal of this chapter is to provide insights/updates on the spatio-temporal dynamics of vegetation cover in Kumasi. More specifically, the study analyzes the vegetation change over time and space using multi-resolution images, explores the current composition of UGS types, and examines possible drivers and injustices associated with UGS distribution in Kumasi, Ghana.

3.2 Methodology

3.2.1 Study area

Kumasi metropolis is located in south central Ghana (6° 41”N, 1° 37”W, Figure 3.1). The climate is tropical, characterized by a bi-modal rainfall system. Mean annual rainfall and temperature are respectively, 1,250 mm (Owusu 2009) and 26.4°C (Manu, Twumasi, and Coleman 2006).

Kumasi is inhabited by > 2 million people with a population density of 8,000 persons per km^2 and an annual growth rate of 4.8 % (Ghana Statistical Service 2012; KMA 2013). It is a central transiting point for travelers from within and beyond Ghana and hosts the largest open market in West Africa (Adarkwa 2011). Due to map generation short-comings, the area considered in this study (178.3 km^2) is less than the 254 km^2 often quoted for Kumasi by the Kumasi Metropolitan Assembly (KMA). A political map of Kumasi displaying the 10 submetropolises is given in Figure 3.1.

3.2.2 Land cover change detection procedures

The vegetation distribution and change in the metropolis were determined by obtaining, processing and analyzing Landsat TM image (December, 1986), Landsat ETM image (April, 2001) and RapidEye images (November, 2009 and January, 2014) (Figure 2A-D). These were the only available relatively cloud-free multispectral images covering the entire study area. High-spatial resolution RapidEye images (5 m) allow detection of minute changes such as clearing of vegetation and erection of new buildings. Both Landsat and RapidEye images were georeferenced to the Universal Transverse Mercator map projection (zone 30N) and radiometrically normalized by United States Geological Survey and Blackbridge AG, respectively.

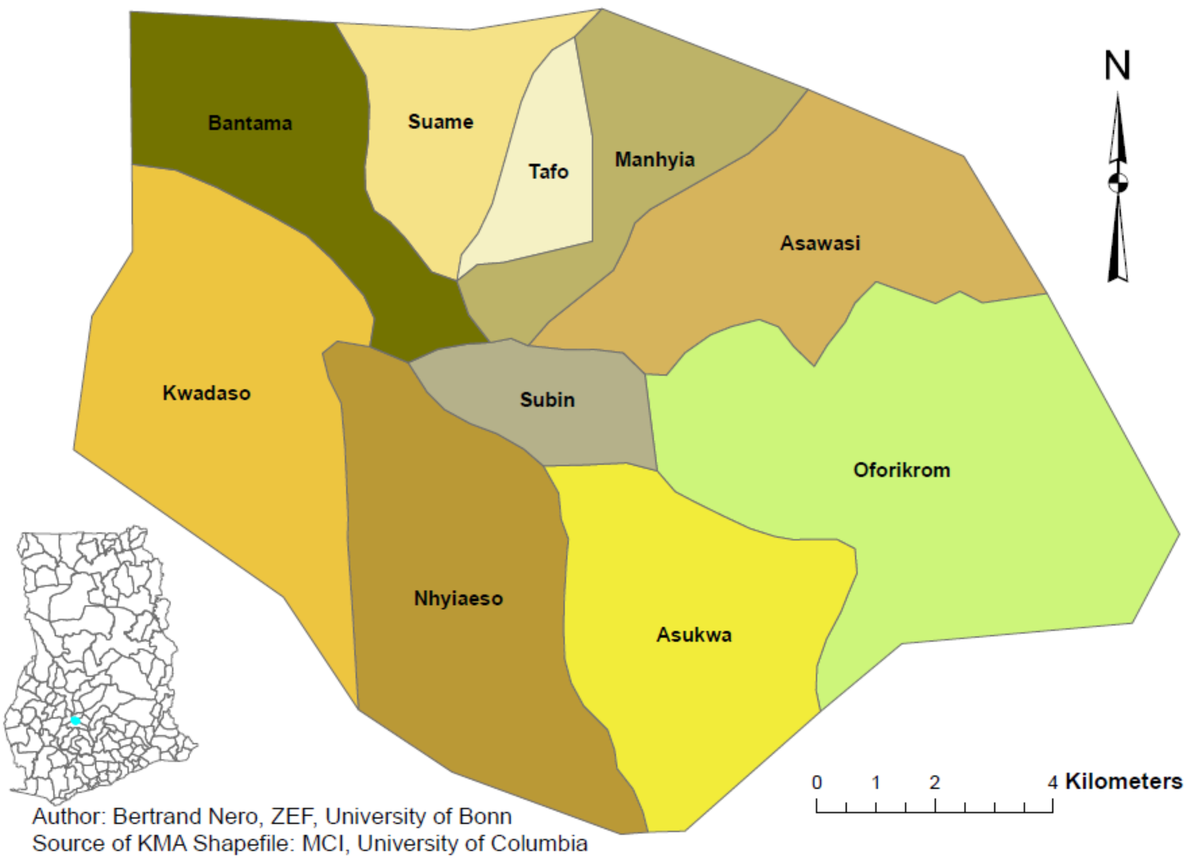


Figure 3.1 Political map of Kumasi metropolis showing the 10 submetropolises.

Simple thresh-hold classification of normalized difference vegetation index (NDVI) values was conducted to generate vegetation proportion maps for all the multi-date images. NDVI is the ratio of the difference between the near infrared (NIR) and red (R) bands to the sum of these bands (NIR + R). The area was classified into vegetation (NDVI > 0.2) and non-vegetation (buildings, bare ground, roads, water) (NDVI < 0.2) on per pixel basis (Stow et al. 2012).

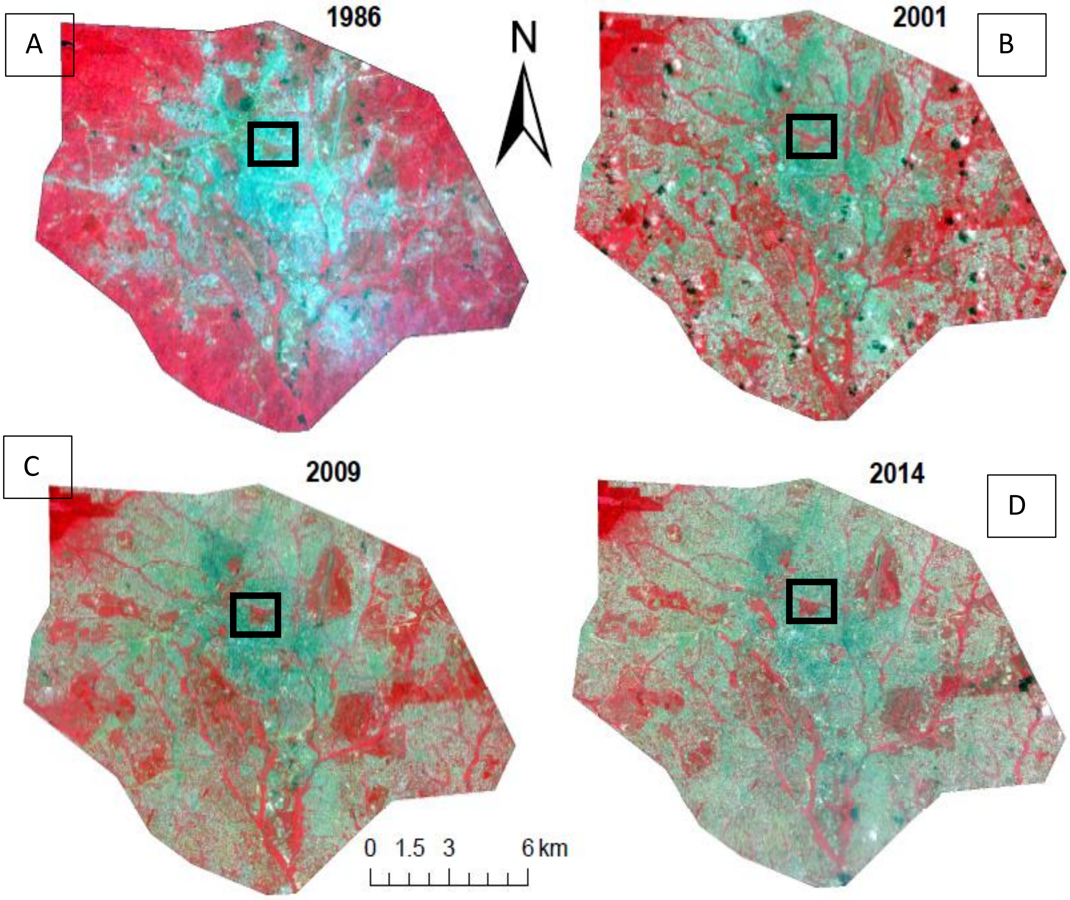


Figure 3.2 False colour images (A – D) for four different years; 1986, 2001, 2009, and 2014; displaying the pattern of land cover change in 28 years in Kumasi. Area encased in black is a park behind the Ashantehene's palace which was bear in 1986 but is now forested.

Furthermore, object-based image classification using eCognition software was performed on the data. The results were visually analyzed and mapped vegetation objects represented on the products of object-based image analysis software were compared to these multi-resolution images displayed in false color. It was obvious that errors associated with the products of the eCognition software were more prevalent than the per pixel NDVI classification. Considering these qualitative observations, the simplicity of the classification approach and the higher quantitative accuracies (reported in the results section), the NDVI classification products were used for further analysis. Supervised (maximum-likelihood) classification was performed on all four NDVI classified products. Up to 150 training data points were collected using stratified random sampling techniques during a field visit to Kumasi for land cover analysis. Equal samples were collected for each land cover class. For images predating 2014, training data were obtained from old land cover and urban plan maps in consultation with local residents. Two interviewers who agreed on the land cover classes based on the historical map objects went out and conducted independent interviews among local residents (over 50 years old) who had lived in the neighborhoods within the last 30 years to ascertain the precision of the training samples. The training data was separated into 100 samples for classification and 50 for validation for each image using split layer tool in ArcGIS. The sample size for validation data was determined based on an overall accuracy target of 90 %, a confidence interval of 95 % and a desired half-width of 8 %.

To provide the current UGS composition and distribution map of Kumasi, a detailed supervised (maximum-likelihood) classification of the 2014 RapidEye image was performed. Up to 12 land uses (including UGS types) were identified and mapped; urban built-up, peri-urban built-up, bare ground, home gardens, institutional compounds, farmlands, grasslands, plantations, natural forest, wetlands (areas that experience inundation at least 14 consecutive days within the year), and water(Appendix 3). A total of 850 ground-truth data points were also collected during a field visit to Kumasi in 2014 for detailed mapping of UGS distribution in the city. Of this total, 365 data points were used for supervised classification and 485 data points for validation and accuracy assessment. A stratified sampling design with land use (UGS) as a stratum was adopted to increase the precision of sample estimates (Levy and Lemeshow 2008). Overall, User's, producer's accuracies, and kappa coefficient were computed from the resulting confusion matrices. All maps satisfied the minimum accuracy standards stipulated in the Anderson classification scheme (Anderson et al. 1976), except the detailed land use/UGS map of the 2014 image. Because detailed classification of images predating 2014 consistently turned out classified images with low overall accuracies < 45 % (high errors of commission and omission), no further analysis were performed using these detailed UGS maps. The large errors (uncertainties) in the classified images predating 2014 stemmed from collocation issues between field observations and pixels, lack of detailed historical land use maps, uncertainties among respondents about the exact historical land uses and the low spatial resolution of Landsat.

Post-classification change detection approach was used for land cover change analysis between 1986 and 2014. The classified land cover maps for the respective years were directly compared. This approach provides descriptive information on the nature of the land use classes and change that occurred. One demerit of this approach is that, the accuracy of the change map depends on the accuracy of the classifications of the individual maps being compared. The proportion of each land cover was estimated by extracting the pixels in each land cover class based on GIS algorithms. Furthermore, the land cover change map was subjected to accuracy assessment, quantification of area and uncertainty using stratified estimation procedures outlined in Olofsson et al. (2013; 2014). Four strata including: stable vegetation cover, stable non-vegetation cover, vegetation loss, and vegetation gain by 2014 were identified on the 1986-2014 change map. A sample size of about 440 was determined based on a targeted standard error of the overall accuracy of 2.5 % and speculated user's accuracies of 0.75, 0.9, 0.95, and 0.95, respectively, for the vegetation gain, vegetation loss, stable non-vegetation, and stable vegetation classes. Speculated user's accuracies were derived from previous urban land cover studies in cities in Ghana. Since vegetation gain was the rarest class, a sample size of 80 was allocated to it following procedures outlined in Olofsson et al. (2014). Equal sample size allocation was applied to the remaining classes since land areas of these classes were almost equal. Data collected during a field visit in 2014 were complemented with sample data extracted from Google Earth™ in conjunction with old land use/cover maps and local knowledge of Kumasi (gathered as described previously) to constitute the reference data for the accuracy assessment of the change map. Following accuracy assessment of the change map, uncertainty of the accuracy and the area estimates were estimated in accord with the good practice guidelines by Olofsson et al. (2014). Accuracy assessment of the 2009-2014 change map was performed with a sample size of 352 following these guidelines above.

Absolute percentage change in land cover between 1986 and 2014 were determined at the citywide scale. Additionally, the proportion of vegetation cover was estimated for each political submetropolitan unit of Kumasi in 2009 and 2014 by summing the area classified as vegetation for each submetropolis and dividing by the total area of each submetropolis. Absolute percentage change in vegetation cover, expressed as the difference in percentage vegetation cover between two time periods, was also computed for each submetropolis for the period of 2009 and 2014. Relative percentage change in vegetation, expressed as the absolute percentage vegetation change between 2009 and 2014 divided by the percent vegetation cover in 2009 for each submetropolis was also computed for each submetropolis. Area coverage for green and tree cover classes (2009 and 2014) were extracted at the submetropolitan level using a political submetropolitan map of the city and the data used for further analysis.

In addition, urban sprawl in 1986 and 2014 were estimated using Shannon entropy (En). Shannon entropy can be used to indicate the degree of spatial concentration and dispersion exhibited by geographic variables (Yeh and Li 2001). It is estimated by defining zones along major roads or by defining buffers from the city center and calculating the built-up area in each zone. The Shannon entropy is calculated as (eq. 3.1):

$$\text{En} = \sum_{i}^{n} pilog(\frac{1}{pi})/\log(n) \qquad (3.1)$$

Where En = Shannon entropy, pi = Xi/$\sum_{i}^{n} Xi$ and Xi is the density of land development = area of built-up divided by total land area in the i^{th} of n total zones, and n is the number of zones from the city center. The value of the entropy ranges from 0 – 1. An index of 0 implies the urban spread is compact whereas an index of 1 implies the urbanization is scattered. To analyse sprawl in Kumasi, the area was divided into six concentric zones. Zones were separated by 2 km radius except for the sixth zone which had a 1 km radius because it was beyond the boundary of the study area.

3.2.3 Socio-economic and vegetation distribution in Kumasi

Principal component analysis (PCA) was employed in creating housing quality index (HQI) for sub-metropolitan areas of Kumasi. Dummy variables were created for all housing and infrastructure characteristics available in the 2010 census at the housing unit and sub-metropolitan levels. Household constituted the unit of analysis for the PCA. The variables considered were: number of separate/self-contained houses, number of compound houses, number of improvised houses, house hold (HH) size, mean number of people sharing a room, number of HH with access to three sleeping rooms, number of HH with access to at least four sleeping rooms, percentage of HH not sharing at least a sleeping room, number of houses with wooden walls and number with concrete cement walls. Other variables include percentage of HH living in rooms with cement floors, earth mud floors, shared bathroom facility, use veranda as cooking space, dispose liquid waste in gutter/drain and percent that depend on public toilets.

Over all, there were 25 variables entered into the PCA, from which four components with an eigenvalue > 1 were extracted, explaining 91 % of the variance in the set of variables. The first and second components had eigenvalues of 11.88 and 7.68 and were significantly larger than the eigenvalues of the other components. The first component alone accounted for 46.2 % of the variance and consisted of nine variables, each of which loaded with coefficients above 0.70. These variables were whether a submetropolis had greater percentage of HH with access to: 1) private water closet toilet facilities at home, 2) used gas for cooking, 3) had a separate space for cooking (lesser usage of veranda as cooking space), 4) disposed their solid waste through collection by an organization, 5) put their liquid waste in sewers, 6) disposed their solid waste through public dumpsites, 7) live in houses with zinc roofing sheets, 8) used charcoal for cooking, and 9) live in houses with asbestos roofing materials. Because factor scores are centered around a mean of zero, with a minimum in this case of -1.91, a constant was added to each score such that the range was from zero (0) for submetropolises with lowest quality of housing to 5 for the highest quality housing. Since there are currently no spatial data at the neighborhood level in Kumasi, the housing and household data were obtained at the submetropolis level. Hence, the factor scores produced here represent the HQI for each submetropolis and used as surrogates for socio-economic standards for each submetropolis.

3.2.4 Inequality in vegetation distribution

Dissimilarity analysis was applied to determine whether UGS are equally distributed among inhabitants in the ten submetropolises in Kumasi. Among the numerous indices often adopted for characterizing inequality in UGS distribution among urban inhabitants, the Gini coefficient was selected for this study. The Gini coefficient is a value between 0 and 1; where 0 represents perfect equality of potential access to green spaces (or the share of UGS are evenly distributed within the city scape) and 1 represents perfect inequality (or the share of UGS is extremely high in fewer submetropolises). Applying the Gini coefficient therefore is a simple way to obtain an overview of the distribution and the relation between green spaces and population. One major caveat of this coefficient is that it is sensitive to changes around the median of the distribution but is silent on the spatial distribution of possible dissimilarities. It was however, successfully applied in evaluating inequality in green space distribution among certain population groups in Berlin (Kabisch and Haase 2014) and in analysis of land use structure in China (Zheng et al. 2013).

The Gini coefficient for the green cover was computed for the entire city using submetropolis level population data. The Gini coefficient is presented as (eq. 3.2):

$$GC = \left[\sum_{i=1}^{k} (U_{i-1} + U_i)p\right] - 1 \qquad (3.2)$$

Where GC = Gini coefficient for green space distribution, p is the relative share of population in the submetropolis, and U is the cumulative share of UGS in the submetropolis.

In addition, a Lorenz curve was constructed using the cumulative proportion of population in the submetropolis (Ghana Statistical Service 2012) and cumulative proportion of UGS and tree cover in each submetropolis obtained from analyses of 2009 and 2014 RapidEye images.

3.2.5 Statistical analysis

Ordinary least square regression was used to analyze the strength of the relationship between HQI from the 2010 census and vegetation cover in 2009 and 2014. Since the data appeared to be normally distributed parametric regression statistics were applied. Diagnostics were performed on the standardized residuals to check for the presence of spatial autocorrelation (based on Moran’s I) and heteroscedasticity (based on Breusch-Pagan test).

3.3 Results

Overall accuracy >89 % and a Kappa coefficient >0.8 were obtained for all the land cover classifications in all four years (images) (Table 3.1). User’s accuracy (accounting for errors of commission) for non-vegetation (bare and built areas) was 84 % in 1986, 87 % in 2014 and 100 %

in 2000 and 2009. For the vegetation (green) cover, the user's accuracy was mostly 100 % except in 1986 when it was 96 %. Producer's accuracies (accounting for errors due to omission) were 81.5 % and 87 % in 1986 and 2014, respectively, and 100 % in the years in between. Non-vegetation cover had producer's accuracy of 100 % for all images (years) classified. Considering the high categorical accuracies, these maps were reliable in portraying the spatial distribution and changes in land cover at the submetropolitan and metropolitan levels. Classified land cover maps for all four years are presented in Figure (3.3 A – D).

Table 3.1 Accuracy assessment results for the land cover classification for all four images (1986, 2001, 2009 & 2014) in Kumasi: user's, producer's, and overall accuracy including kappa coefficients are presented in each case.

	Reference or Ground-truth data					
Classification 1986	Vegetation	Non-vegetation	Water bodies	Total	User's Accuracy	Producer's Accuracy
Vegetation	22	0	1	23	95.7	81.5
Non-vegetation	5	26	0	31	83.9	100.0
Water bodies	0	0	2	2	100.0	66.7
Total	27	26	3	56		
Overall Accuracy		89.3	kappa Coefficient		0.80	
2001	Vegetation	Non-vegetation		Total	User's Accuracy	Producer's Accuracy
Vegetation	23	0		23	100	100
Non-vegetation	0	24		24	100	100
Total	23	24		47		
Overall Accuracy		100	kappa Coefficient		1	
2009	Vegetation	Non-vegetation		Total	User's Accuracy	Producer's Accuracy
Vegetation	30	0		30	100	100
Non-vegetation	0	26		26	100	100
Total	30	26				
Overall Accuracy		100	kappa Coefficient		1	
2014	Vegetation	Non-vegetation		Total	User's Accuracy	Producer's Accuracy
Vegetation	26	0		26	100.0	86.7
Non-vegetation	4	26		30	86.7	100.0
Total	30	26		56		
Overall Accuracy		92.9	kappa Coefficient		0.86	

The magnitude of vegetation and non-vegetation cover change from 1986 to 2014 for the entire study area are presented in Table 3.2. Absolute percentage vegetation (green) cover decreased by 25.6 % within 28 years in Kumasi metropolis. Absolute percentage vegetation cover decline in the last five years (2009-2014), at 16.8 % was about four (4) times greater than the change that occurred between 1986 and 2001 (4.7 %). This amounts to a loss of 4,530 ha of vegetation cover between 1986 and 2014, 2,980 ha loss between 2009 and 2014 and 833 ha loss between 1986 and 2001. The area of vegetation cover decreased by 44 % between 1986 and 2014 while the non-vegetation area increased by 61 %. Furthermore, in almost 30 years, the vegetation cover declined by 0.5 folds whiles the non-vegetated area and population increased by 1.6 and 4.6 folds, respectively, within the Kumasi metropolis (Table 3.2). Per capita green area declined by 8 folds from 200 m^2 per person in 1986 to 25 m^2 per person in 2014.

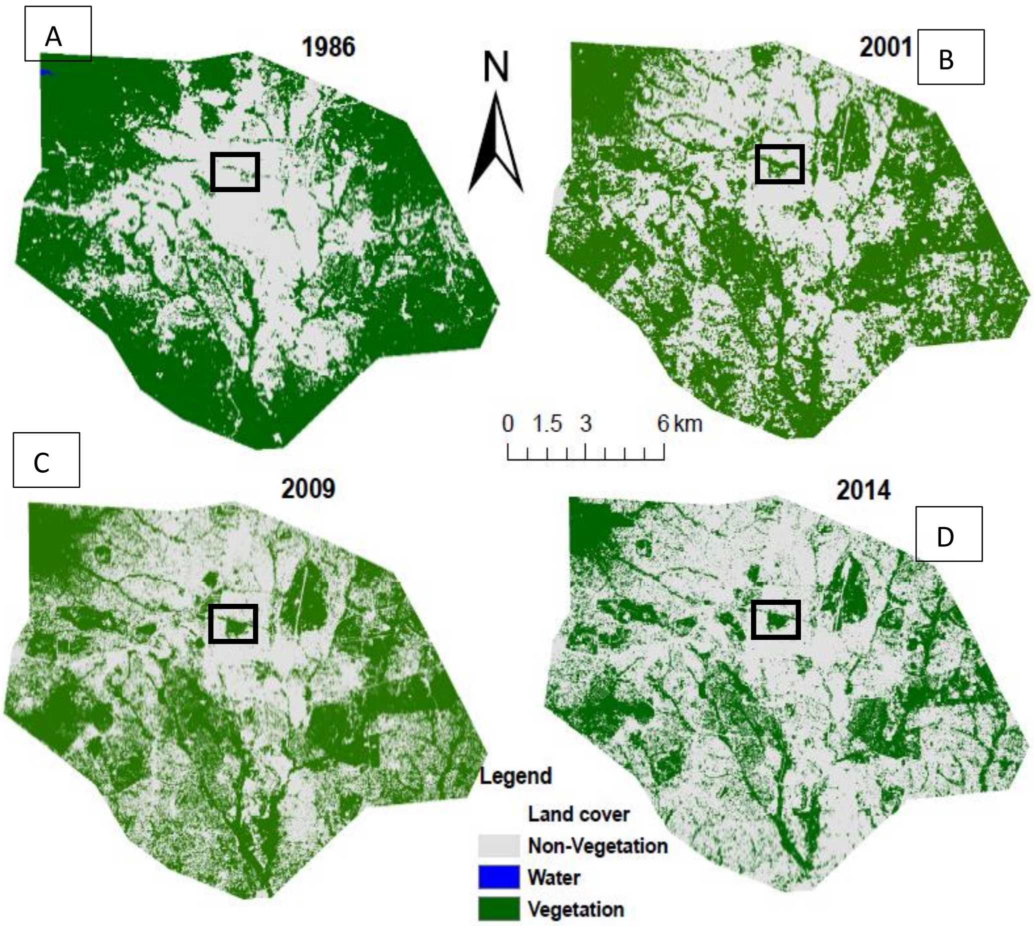


Figure 3.3 urban land cover maps (A - D) for four different years: 1986, 2001, 2009, and 2014, displaying the pattern of land cover change in 28 years in Kumasi. Area encased in black is a park behind the Ashantehene’s palace which was bear in 1986 but is now forested.

Table 3.2 Change in land cover (ha), population and per capita vegetation (green space) area in the Kumasi metropolitan area between 1986 and 2014

Land Cover	1886	2001	2009	2014	Absolute % Change (2014-1986)
Non-vegetation	7,444	8,282	8,979	11,959	25.6
Vegetation	10,378	9,545	8,777	5,796	-25.6
Water bodies	6	0.0	0.0	0.0	0.0
Total	17,828	17,827	17,756	17,756	0.0
% Green cover	58	54	49	33	-25.6
Population	51,4371	1,300,072	1,878,675	2,342,405	0.0
Green space per capita (m^2/person)	202	73	47	25	-177

[1]1986 and 2002 images are from Landsat whiles 2009 and 2014 are from RapidEye.

In 1986, the central part of Kumasi metropolitan area was non-vegetated while the outskirts especially in the west and east had a denser vegetation cover with bits of vegetation in the north and south ends of the city area (Figures 3.2 and 3.3). By 2001, the sparse vegetation in the north and south ends of the city had disappeared almost completely whilst non-vegetation cover displaced the dense green cover in the east and west by 2009 with more severe vegetation cover loss in the last five years leading to the present UGS cover of 33 % by 2014. Currently the most extensive vegetation cover is located at the north-west corner of the city, mainly in the Owabi wildlife sanctuary. A small patch of green cover still exists in the middle of the eastern part of the city. The maps also revealed that whilst much of the vegetation in the city fringes have been replaced by grey infrastructure (buildings, roads, and other compacted surfaces), green patches in the older middle parts of the city are emerging (Figures 3.2 and 3.3). A visible example is noticed around the Asantehene's (the king's) palace, encircled in black (Figures 3.2 and 3.3), which was bare in 1986 but is now green as a result of the establishment of a tree plantation within the past 20 years. The resurgence in green cover in areas that were previously grey is a reflection of renewed interest by public and private institution/organizations in maintaining an environmentally friendly city. Schools in particular have resorted to planting tall trees on their compounds to provide shade and protect roofs from being ripped by violent winds.

Accuracy assessment of the land change map is presented in table 3.3. The overall accuracy is 96±2 % while the producer's and user's accuracies range between 75±9 % and 99±2 %. These reflect the precision and reliability of the change map. Overall, 1,448 ha were converted from non-vegetated area to vegetation cover while 5,967 ha were converted from vegetation cover to non-vegetation cover between 1986 and 2014 (Table 3.4). Substantial amounts of the vegetation and non-vegetation land cover classes remained unconverted within the 28 year period.

Table 3.3 Error matrix of the area proportions of 1986-2014 change map with sample counts shown in parenthesis. Map categories are rows and reference categories are the columns. Accuracy measures are presented with 95% confidence interval and the overall accuracy was 0.96±0.02.

	Vegetation gain	Vegetation loss	Stable non-vegetation	Stable vegetation	Total	User's accuracy	Producer's accuracy
Vegetation gain	0.061 (60)	0.003 (3)	0.017 (17)	0.000	0.082 (80)	0.75±0.09	0.91±0.07
Vegetation loss	0.000	0.328 (117)	0.000	0.008 (3)	0.336 (120)	0.97±0.03	0.99±0.02
Stable non-vegetation	0.000	0.331	0.332 (118)	0.006 (2)	0.337 (120)	0.98±0.02	0.95±0.04
Stable vegetation	0.006 (3)	0.000	0.000	0.239 (117)	0.337 (120)	0.97±0.03	0.94±0.04
Total	0.067 (63)	0.331(120)	0.349(135)	0.253 (122)	1.000 (440)		

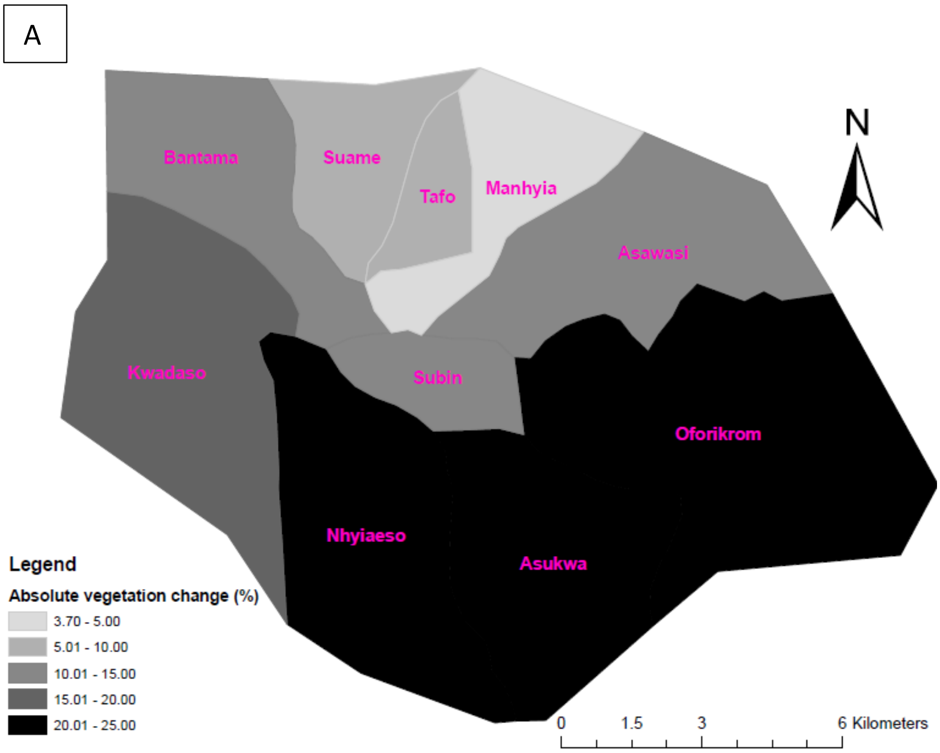
Table 3.4 Land cover mapped area, adjusted area, proportion of mapped area of land cover i (Wi), and margin of error of the 1986-2014 change map.

Land cover	Mapped area (ha)	Adjusted area (ha)	Margin of error 95% CI	Wi
Vegetation gain	1,448	1,195	±265.5	0.082
Vegetation loss	5,967	5,872	±232.7	0.336
Stable non-vegetation	5,992	6,200	±273.9	0.337
Stable vegetation	4,348	4,488	±435.9	0.245

Wi = mapped area of land cover i / total area of map

The absolute and relative percentage vegetation change for the ten submetropolises are presented in Figure 3.4. Absolute percentage vegetation change was < 10 % in Menhyia, Suame and Tafo and > 20 % in Asukwa, Oforikrom, and Nhyieaso between 2009 and 2014. Relative percentage vegetation change was in the range of 19 – 45 % with Menhyia undergoing the least relative change in vegetation (<20 %) whiles that of Suame, Asukwa, and Nhyieaso was > 40 %.

The non-vegetation (built-up, bare areas, roads etc) area density in Kumasi decreased with distance from the city center. In 1986, the non-vegetation cover density was at least 80 % within 4 km from the city center and declined steeply to 43 % at 6 km, to 11 % at 8 km with areas within 11 km from the city center holding 5 % of non-vegetation cover. However, by 2014, the non-vegetation (brown) area density in the city was generally very high regardless of distance, with the range 8 – 10 km from the city center having the lowest non-vegetation cover of 48 % (Figure 3.5). This is reflected in the high Shannon entropies of 0.994 in 2014 and 0.801 in 1986. The high Shannon entropies in both years suggests that Kumasi is traditionally a sprawled rather than a compact city. However, non-vegetation area density has become more intense and uniformly distributed with distance from the city center in recent years (2014) than in 1986. In 1986, the city's outskirts were more densely vegetated than in 2014.



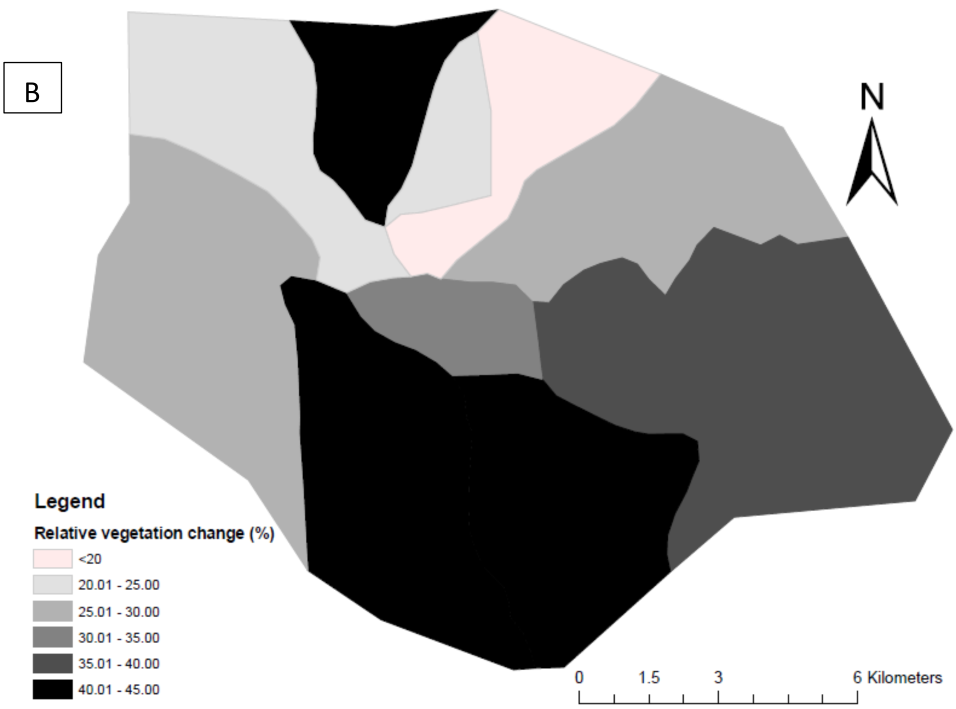


Figure 3.**4** Percentage vegetation change within each submetropolis: (A) absolute vegetation change (% vegetation in 2009 - % vegetation in 2014) and (B) relative vegetation change (absolute vegetation change divided by % vegetation in 2009).

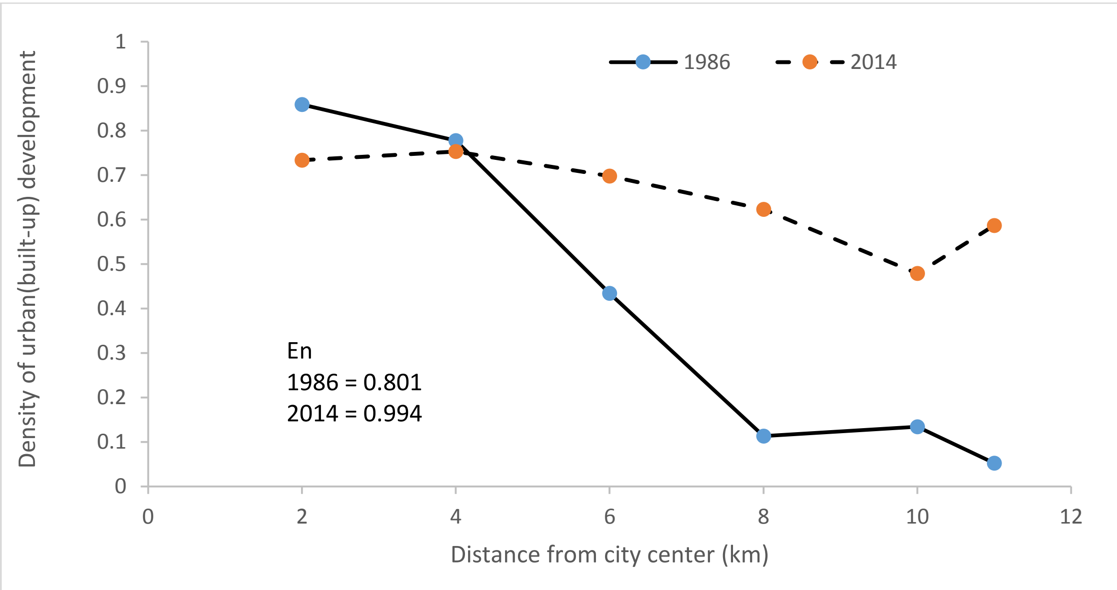


Figure 3.**5** Density of urban non-vegetation (built-up or brown cover) development from the center of the city towards the periphery. Shannon entropies for built-up sprawl are indicated.

Table 3.5 Error matrix for land use /green space classification of 2014 image of Kumasi metropolis. The 95% confidence intervals of the user's and producer's accuracies are indicated. Kappa = 0.56, Overall Accuracy = 62.3±5.5%.

	Reference or Ground-truth data													
Classification	Plantation	Natural Forest	Home garden	Farmland	Urban built-up	Peri_urban built-up	Grass_ upland	Grass_ wetland	Grass_ lawn/lowland	Bare ground	Water	Institutional compound	Total	User's Accuracy
Plantation	53	2	3	5	0	0	0	0	0	0	0	1	64	82.8±9.3
Natural forest	2	6	0	2	0	0	0	0	0	0	0	1	11	54.5±29.5
Home garden	4	0	44	5	0	1	3	1	2	0	0	18	78	56.4±11.0
Farmland	11	0	5	31	0	0	0	1	0	0	0	4	52	59.6±13.4
Urban built-up	3	0	10	0	27	3	0	0	0	2	0	5	50	54.0±13.8
Peri-urban built-up	0	0	0	0	0	11	0	0	0	1	0	0	12	91.7±15.7
Grass_upland	3	1	**5**	2	0	0	23	0	0	0	0	0	34	67.6±15.7
Grass_wetland	2	0	0	1		0	0	14	0	0	0	0	17	82.4±18.2
Grass_lawn/lowland	1	0	3	4	0	0	0	1	17	1	0	0	27	63.0±18.2
Bare ground	0	0	3	1	3	0	0	0	0	9	0	1	17	52.9±23.8
Water	0	0	0	0	0	0	0	0	0	0	6	0	6	100.0±0.1
Institutional compound	20	0	24	10	0	0	0	1	0	1	0	61	117	52.1±9.1
Total	99	9	97	61	30	15	26	18	19	14	6	91	485	
Producer's Accuracy	53.5±9.8	66.7±30.9	45.4±9.9	50.8±12.6	90.0±10.8	73.3±22.4	88.5±12.3	77.8±19.2	89.5±13.8	64.3±25.1	100.0±0.1	67.0±9.7		

The overall accuracy and Kappa coefficient of the green space types and grey/brown cover classification of Kumasi (2014 RapidEye image) were 62.3 % and 0.56, respectively (Table 3.5). The user's accuracies for all UGS types were at least 52 %, with the lowest associated with the institutional compounds. The lowest producer's accuracy was 45 % and occurred in home gardens while the highest was 100 % in the water bodies land use class. Low producer accuracies in home gardens, farmlands, plantations (range 45 – 54 %) were a result of overlap of several land use classes due to similarity in spectral signatures. Considering the moderate to high categorical accuracies, the green space distribution map (Figure 3.6) is moderately reliable in portraying the spatial distribution of green spaces in Kumasi metropolis.

Eight different UGS types (excluding urban and peri-urban built-up areas, bare ground, water bodies) distributed across the Kumasi metropolitan area are presented in Figure 3.6 while the percent area extent of each UGS type is in table 3.6. Home gardens which consisted of lawns, crops and/or trees were the most dominant UGS type in the city, accounting for 46 % of green area and particularly common in the core urban area. Vegetation on institutional compounds was the 2nd most common UGS type, constituting 18 % of the green area in the metropolis. Institutions in this context refer to both public and private established organizations with some landed property, e.g. schools, hospitals, churches, public administrative office premises. Range /grasslands, which include grass_lawns/lowlands, grass_uplands, and grass_wetlands (Figure 3.6), is the 3rd most extensive UGS type, constituting about 17 % of the total green area in the metropolis. Farmlands constituted about 8 % of the entire green area of Kumasi, while plantations, natural forest, public parks and cemeteries were respectively 7 %, 3 %, 1 % and <1 %. The total green area within the KMA political boundary is about 5,796 ha. However, when a 2 km radius around the KMA boundary is included (Figure 3.6), the green area sums up to about 17,597 ha out of a total area of about 30,000 ha. The Owabi wildlife sanctuary behind Bantama submetropolis greatly influences the green cover of Kumasi. A detailed description of each UGS type in terms of vegetation structure is presented in Appendix 3.

Table 3.6 Percent area coverage of the different green space types in Kumasi metropolitan area.

UGS Type	Land Area (ha)	Percent UGS Area (%)
Home garden	8,106	46.1
Plantation	1,146	6.5
Natural forest	602	3.4
Institutional compound	3,140	17.8
Cemetery	41	0.2
Farmland	1,464	8.3
Grassland	2,908	16.5
Public parks	191	1.1

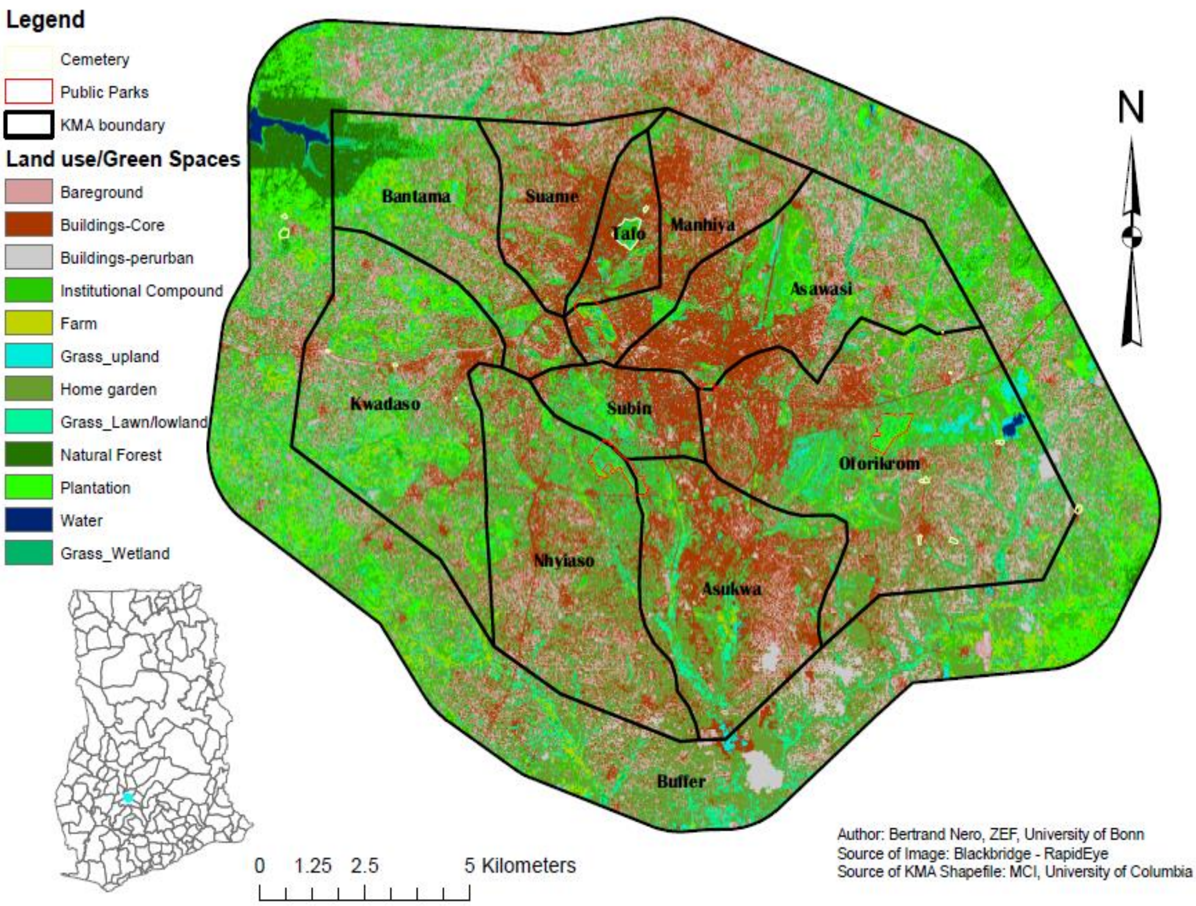


Figure 3.**6** Green space distribution map of Kumasi metropolitan area and its enclaves.

Scatterplots and statistical results from regressing per capita green space area against HQI are shown in Figures 3.7A and 3.7B. HQI was treated as the independent variable because it is not influenced by other variables considered in the study. However, altering the quantity of HQI affects green space per capita, green space area, absolute and relative change in green space area. Hence, these variables were considered the dependent variables. An average degree of spatial covariability for HQI and per capita vegetation cover is evident based on r^2 values of 0.50 (n=8, p=0.049) and 0.53 (n=8, p=0.0398) for 2009 and 2014 per capita vegetation cover, respectively. Low spatial covariability (r^2 <0.1) was obtained when percent vegetation cover was regressed against HQI in both 2009 and 2014 (data not shown). These results suggest that the relationship between HQI and vegetation cover (percent or per capita) is not robust and relatively unaffected by the changing vegetation over the span of time covered in this analysis. Analysis of standardized residuals from the model revealed no spatial autocorrelation and heteroscedasticity. Furthermore, no significant relationship was found when absolute and relative percent vegetation change were regressed against HQI, respectively.

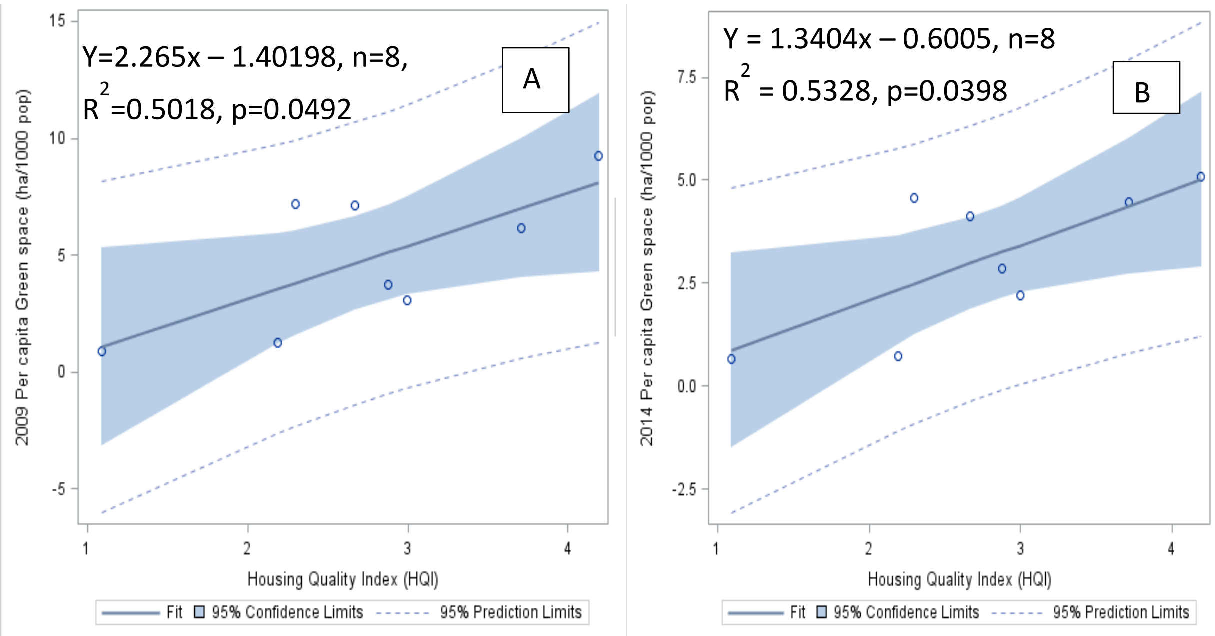
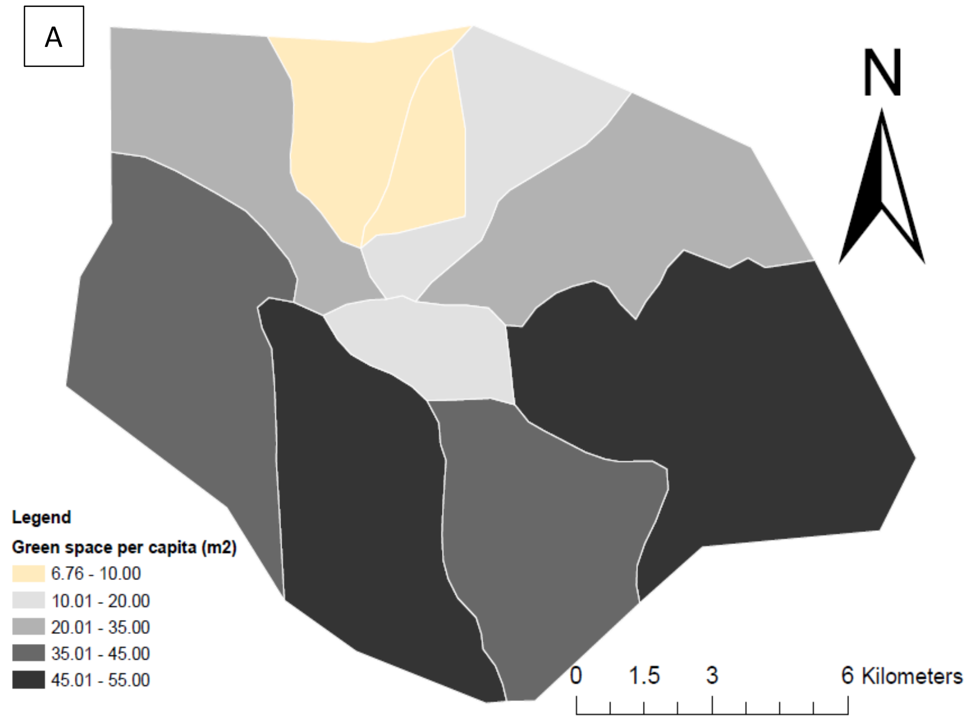


Figure 3.7 Scatter plots, least square regression lines, and regression statistics for submetropolis-level analysis of (A) Housing quality Index (HQI) versus 2009 green area per capita (ha/1,000 population); (B) HQI versus 2014 green area per capita (ha/1,000 population).

To some extent, the green space area per capita is inversely related to the population density of submetropolitan areas (Figure 3.8). Submetropolises in the southcentral and southeastern parts of the city had the lowest population density and the highest vegetation cover per individual. For instance, Oforikrom, Asokwa, and

Nhyiaeso which had the lowest population densities (< 80 people/ha) had the highest per capita vegetation cover of at least 45 m^2. The northern and central parts of the city which had the highest population densities also tended to have the lowest green space area per individual.



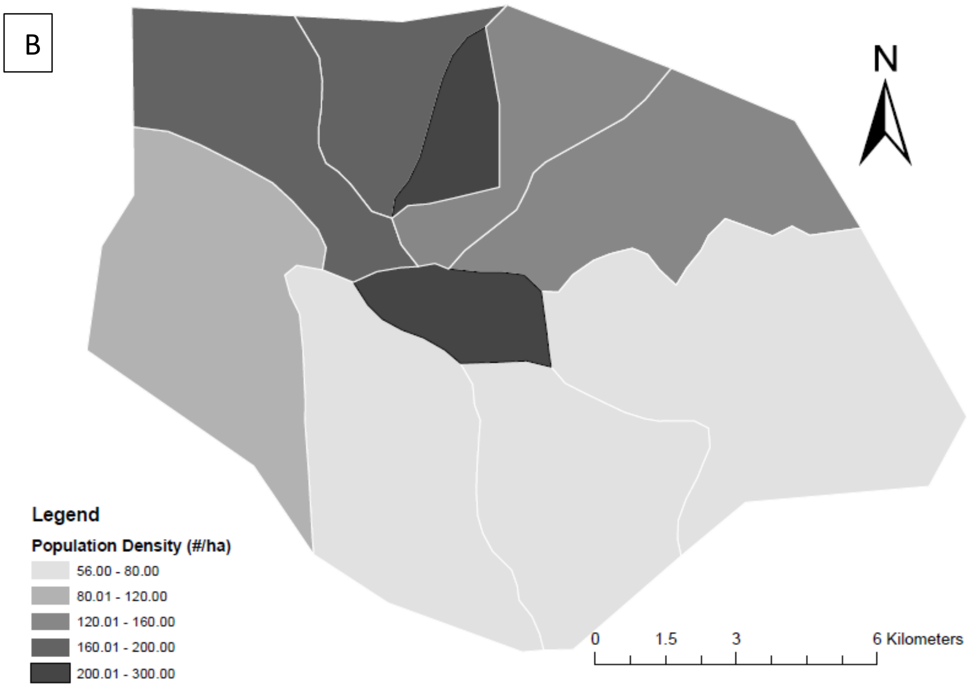


Figure 3.8 (A) Green space per capita and (B) population density distribution at the submetropolis level in the Kumasi metropolis. City mean green space per capita = 25.5 m^2 and mean population density = 114 people/ha.

The Lorenz curve and the Gini index (GI) are common metrics used to measure equality in societies. The amount of deviation (level of separation) between the Lorenz curve and the line of absolute equality (line with 45° slope) indicates the level of inequality (Figure 3.9). In other words, the further the Lorenz curve is from the line of absolute equality, the more unequal the green space distribution among citizens. In Kumasi, there was somewhat unequal distribution of UGS and tree cover among the populace at the submetropolis level: about 25 % of the population is associated (or owns) with 10 % of the green cover and similarly 50 % of green/tree cover is associated with 67 % of the population. The GI of 26 % indicates that the share of UGS and tree cover were somewhat evenly distributed within the city scape of Kumasi.

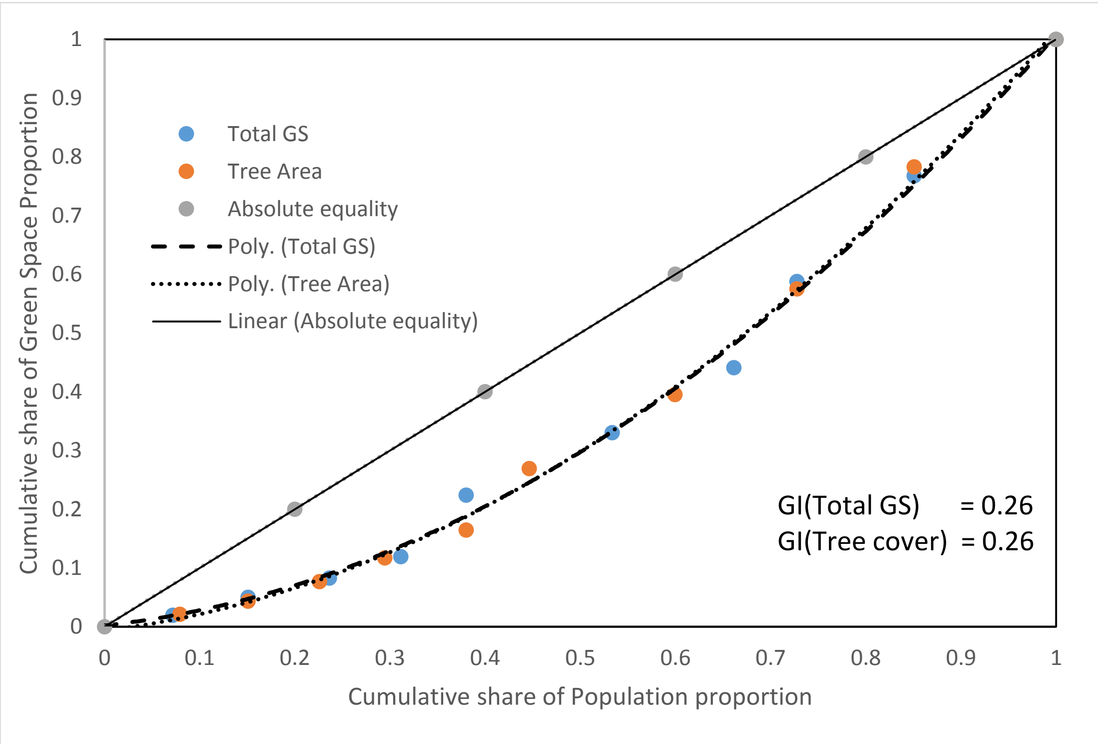


Figure 3.9 The Lorenz curve for total green space (GS) cover and tree cover associated with the population at sub-metropolitan level in Kumasi. Gini index (GI) of the green space cover and tree cover are indicated.

Regressing green space area on population and total land area at the submetropolis level, revealed a moderate relationship (r^2=0.56, n=9) in the former and a strong relationship (r^2=0.9466, n=10) in the latter (Figures 3.10 and 3.11). This corroborates earlier findings that areas with low population density had high green space area per capita (Figure 3.8). Hence, the proportion of a city's green cover depends more on the land area of the city and not necessarily on the population.

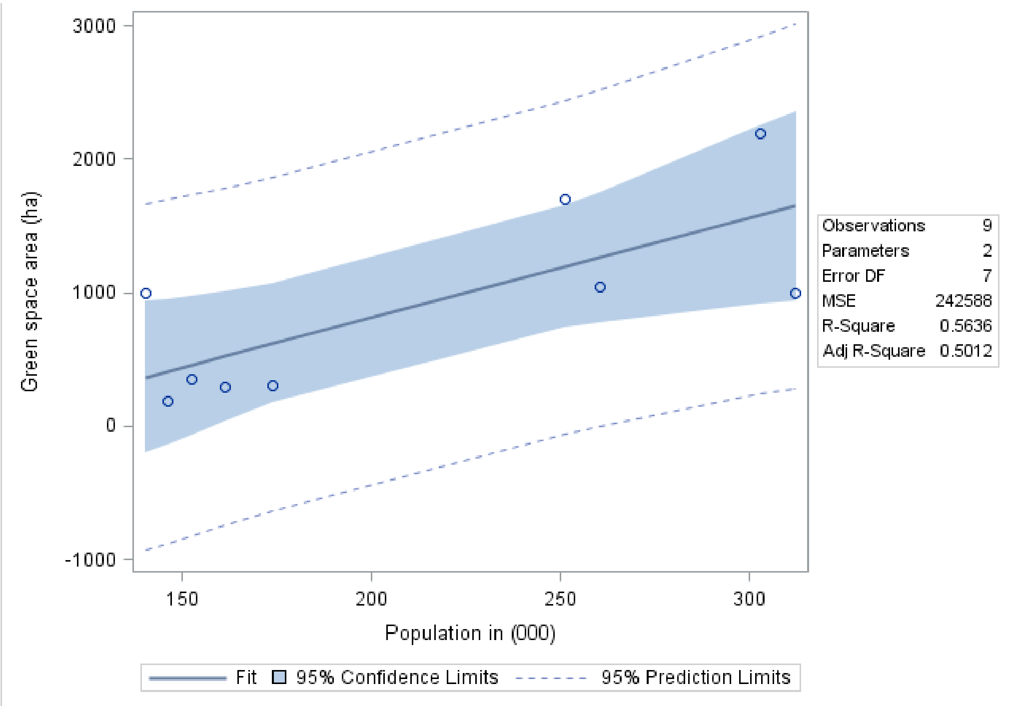


Figure 3.10 Relationship between submetropolis population and green space area in Kumasi, Ghana (p=0.0198, n=9).

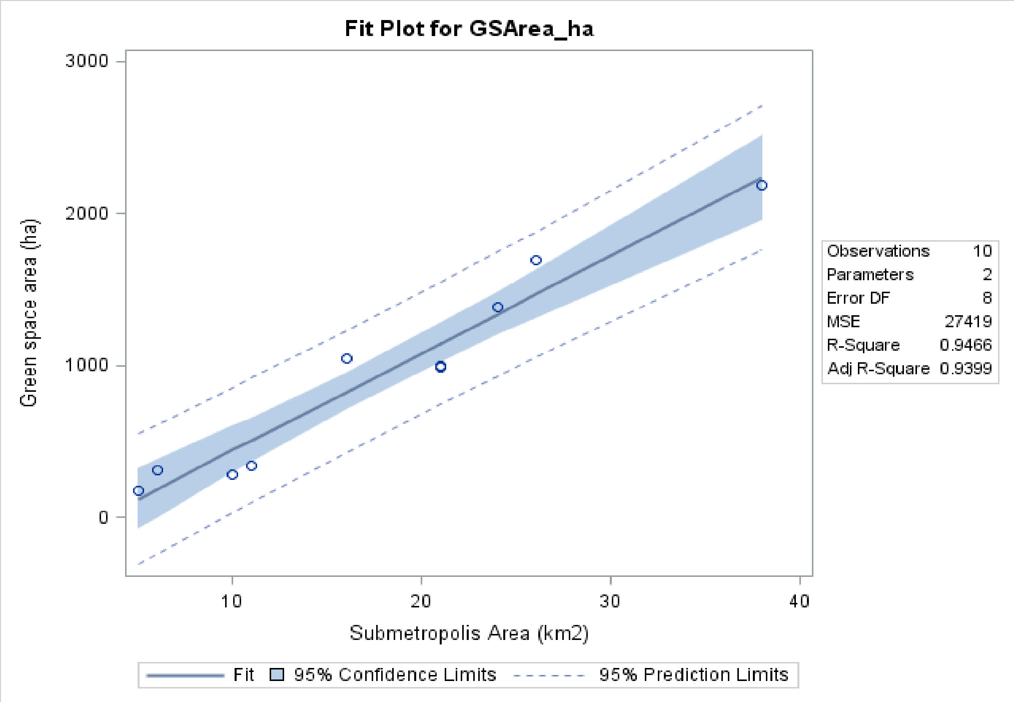


Figure 3.**11** Relationship between submetropolis green space area and submetropolis area in the Kumasi metropolis (p<0.0001, n=10).

3.4 Discussion

3.4.1 Green space decline and urban sprawl

The deterioration of urban vegetation cover in favour of built-up and bare areas has become a common lore in Ghana and needs regular monitoring. This may require the use of multi-resolution images to capture historic land cover patterns and the detailed processes of current land cover changes. In Kumasi, spatio-temporal analysis of vegetation cover between 1986 (Landsat) and 2014 (RapidEye) revealed massive decline in the vegetation cover with the last five years (2009-2014) witnessing the most dramatic vegetation loss rates. Accuracy assessment of our estimates were high (> 89 %) with relatively small standard errors, suggesting that maps generated from these multi-resolution images were reliable. For planning and management purposes, accuracy of land cover classification should be at least 85 % (J. R. Anderson et al. 1976). This reinforces the significance of NDVI based pixel remote sensing and the use of multi-resolution images in analyzing temporal land cover dynamics in urban landscapes where a complex mix of land uses coexist. NDVI-based image classification techniques were successfully applied in urban vegetation change studies in many cities in Ghana (Braimoh and Vlek 2004; Stow et al. 2012; Aduah and Baffoe 2013) although none used mixed resolution imagery nor did any measure uncertainty of the changes detected. Due to the differences in resolution, higher resolution images tend to capture more precise details of land cover and area than the medium-resolution images and hence provide better estimates of change. Furthermore, the change map of Kumasi in this study elicited high accuracy estimates, low standard errors, and mapped area estimates were within the 95 % confidence interval of the reference or adjusted area estimates. These presuppose that the measurement bias associated with the mapped area estimated using pixel counting and the uncertainty due to sampling variability were minimal and that mapped outcomes were consistent. Detecting significantly large changes in vegetation gain and loss especially within a span of 5 years (2009-2014) can be attributed to relatively large accuracies in mapping and adequate accuracy assessment sample sizes (McRoberts and Walters 2012). Amidst budget and time limitations, city environments are readily traversable, making it possible to sample as thoroughly as desired. The high accuracies of these change maps and low biases of area estimates suggest that NDVI-based pixel techniques are comparable to map products of sophisticated techniques such as object-based image analysis and spectral mixtures.

Increased population, high inequality, and disregard for the city plan account for the loss in vegetation cover in Kumasi (Tontoh 2011). As the most vibrant commercial city in Ghana coupled with its strategic central location, Kumasi is the destination of people of all walks of life. Consequently, its population quadrupled between 1986 and 2014 due mainly to natural increase resulting from high fertility and better health care within cities and rural-urban migration. This triggered the large expansion in built-up area, culminating in the massive loss in vegetation cover between 1986 and 2014 and especially so in recent years. The boom in the housing industry in recent years owed much to the high demand for residential and student hostel facilities provoked an inexpedient conversion of natural land to buildings by private individuals and estate developers. This peculiar situation may have accounted for the high absolute percentage vegetation cover loss in submetropolises such as Oforikrom, Asukwa and Kwadaso which host major tertiary institutions in the city and had prior to 2000 been densely vegetated. However, it must be noted that the existence of bare ground which is a major component of the non-vegetated land cover may be a legacy of the culture of neglect and lack of interest in green spaces.

Sprawl analysis indicated high entropy values of 0.80 and 0.99 for 1986 and 2014, respectively, suggesting that Kumasi has for long been a sprawled metropolis. Sprawl is attributed to the housing culture and the pattern of development adopted in this city. Historically, the middle class and the wealthy had a disdain for vegetation in the city because vegetation served as habitat for dangerous wild animals e.g. snakes, scorpions etc and as hideouts for criminals. As a result, old towns such as Tafo, Suame, Manhyia etc were (are still) devoid of vegetation. However, high congestion, depreciating environmental conditions in these old core urban zones, improving economic conditions and the quest for privacy have led to many elites in Kumasi relocating to the peri-urban areas. This practice explains the scattered and nucleated development congregated in the outskirts of the city, characterized by self-contained gated houses with large compounds maintained as green spaces (Cobbinah and Amoako 2014). Although infill densification is still high, there are conscious efforts to convert bare and vacant areas in the core (old towns) urban zones to vegetation cover. This clarifies the difference in built-up density within 4 to 6 km from the city center and the gain in vegetation cover of about 1,448 ha between 1986 and 2014. However, the current population and housing growth rates of 5.7 and 2.4 percent per annum, respectively (Afrane and Asamoah 2011), highlight a housing deficit. Meeting this deficit could further compromise green cover within Kumasi and its enclaves. Adequate urban plans and housing schemes must be invoked by government, administrators and private developers to satisfy the service needs of the city without compromising the boundaries and vegetation relics in the city.

3.4.2 Green space composition and distribution

The overall accuracy and some of the producer's and user's accuracies of the green space/land use map of Kumasi in 2014 (Figure 3.6) were lower than the recommended 0.85 (Anderson et al. 1976). Several reasons may account for this: 1) confusion between green space classes since these were not intrinsically discrete, 2) inherent characteristics of GPS receivers may have resulted in sample points being associated with incorrect pixels, and 3) similarity or indistinguishability in the spectral signatures of green spaces/land uses classes. Other reasons for low map accuracies are discussed in McRoberts (2011). A thorough examination of the reference data in the current study indicated that home garden sample classes were erroneously classified as institutional compounds, urban built-up or peri-urban built-up on the map due to similarity in spectral signatures and other reasons cited above. These were not surprising because a small house garden may be captured as built-up area by the sensor whiles the vegetation within institutional compound and the home gardens are only semantically different but practically the same. Considering these accuracy estimates, the green space map is moderately precise. Hence, map products should be used with caution.

UGS are a reminder of our innate intimate rapport with nature. The variety of UGS types therefore reflects the complex diversity of interest groups co-habiting in urban landscapes. Home gardens for instance are maintained for different reasons: to the wealthy for mere aesthetics and other environmental reasons and to the middle class and the less privileged for alimentary, shade, protection, boundary demarcations, and other cultural services. The culture of maintaining small – large back or front yard gardens near both private and public residential houses explain the extensive cover of home gardens in this city. Due to historical, high congestion and high demand for land, UGS in the core urban area are characteristically smaller in sizes compared to those of the peri-urban area. The existence of home gardens and institutional compound vegetation are however without policy and legal backing and hence are at risk of being converted to grey infrastructure.

Public parks which constitute about 1 % of the green cover of Kumasi and street trees remain the only green spaces directly under government jurisdiction and "managed" by the local government. Except for five functionally upright public spaces (i.e. the Otumfuo park, Kwame Nkrumah University of Science and Technology (KNUST) botanical gardens, the Kumasi zoo, the Royal Golf Course, and the Rattray park) all the other colonially designated public parks have either disappeared or been abandoned

(Mensah 2014a). It is essential to increase the awareness on the value of UGS and strengthen stakeholder participation and institutional capacities engaged in UGS management. UGS discourse especially in this part of the world should encompass non-public green spaces. This will be essential in the strife to satisfy tenet 7 of the sustainable development goal 11 on green space availability and accessibility by all in cities. The skewed location of public spaces and variations in home garden sizes and distribution could incite environmental conflicts as we awaken to the realization of our stakes in their values.

3.4.3 Green space distribution and equity

Green spaces are essential for the wellbeing of urban communities ecologically, socially and economically. However, in many developing countries, their distribution (or access), maintenance, and value are often downplayed mainly due to negligence and overreliance on the hinterlands, culminating in the disappearance, deterioration, and misuse of once glamorous and elaborate public green spaces in "Garden Cities" such as Kumasi (Mensah 2014a). Uneven distribution can create restrictions in access to green spaces or their services and hence compromise the achievement of the SDG target 11.7 and potentially degenerate into environmental injustice.

Mean green space per capita in Kumasi is about 25 m^2 per individual and varies among submetropolises. In contrast to the traditional worldview that urban green spaces are synonymous to public parks and gardens, the green spaces in this study are contextualized to include both public and private green spaces. This contextualization stems from the fact that: 1) public spaces which once were the premise for Kumasi's status as a "Garden City", currently consist of only five functional parks and constitute about 1 % of vegetation cover in the city; and 2) much of the remnant green cover of Kumasi is private green space. Therefore, per capita green space comparisons between cities should be done with enormous caution, since in addition to the above consideration, city form and population have a dovetail influence on this metric. The findings of this study closely corroborate mean green space per capita of 36.5 m^2 in ten

South African towns (McConnachie and Shackleton 2008), far below the mean of 122 m^2 green space per inhabitant observed in medium-sized (> 1 million inhabitants) cities in Africa (Chapter 2), well above the WHO recommended 9 m^2 green space per individual and is within the range of United Nations recommended 30 m^2 green space per capita (Laghai and Bahmanpour 2012; Khalil 2014). It is also within the range of per capita green space (6 – 422 m^2 per individual) for European cities for green spaces (+ forest) (Table 3.5, Kabisch et al. 2015) and between 1.9 - 52 m^2 per person for South American cities (SustainableCitiesNetwork, 2011). In the UK, it is recommended that households live within 300 m from the nearest public park with cities like Sheffield hosting 64 % of households who contravene this rule (Barbosa et al. 2007). It must be noted that availability of green spaces is a function of city area. Hence compact cities will tend to have low per capita green space area (Fuller and Gaston 2009), further confirming the strong relationship between submetropolitan area and green space area in Kumasi metropolis. The differences in per capita green spaces among submetropolises in Kumasi is a subtle indication of distributive injustice.

Table 3.2 Per capita green spaces of cities across Europe. Numbers in parentheses are per capita green spaces when forest area is excluded.

City	Country	Per capita green space (m^2/person)	Source
Amsterdam	Netherlands	14	Beatley 2000
Malmo	Sweden	99 (89)	Kabisch et al. 2015
Berlin	Germany	60 (16.3)	Kabisch et al. 2015
Ljubljana	Slovenia	422 (9)	Kabisch et al. 2015
Bari	Italy	6 (5.8)	Kabisch et al. 2015
Edinburgh	United Kingd.	60 (31)	Kabisch et al. 2015
Lodz	Poland	60 (12.5)	Kabisch et al. 2015

The amount of green space per individual and the proportion of public parks and open spaces (the commons) elicit the city's sustainability status (Chiesura 2004) and can constitute environmental injustice (Kabisch and Haase 2014). In many cities in Europe and North America, luxuriant green space extent is often associated with the wealthy class because of their ability to meet expensive cost of maintenance (Kabisch and Haase 2014; Heynen et al. 2006; Wen et al. 2013). However, conflicting results about the luxury-nature hypothesis do exist (Jennings et al. 2012; Wolch et al. 2014). In Boston and several other US cities, environmental injustice among wealthy neighborhoods are quite common (Pickett et al. 2008). Also, in South African towns and cities, negative correlations between income levels, quality and area of green spaces are ostensible (McConnachie and Shackleton 2008).

The results of this study depict moderate relationships between per capita green space and socioeconomic variables and no relationships between green space area (relative or absolute) and SE condition of the submetropolis. Lack of strong correlation between UGS and SE in Kumasi contradicts findings in neighborhoods in Accra where UGS cover positively correlated with socio-economic conditions (Stow et al. 2012). Each submetropolis consists of several neighborhoods of varying socio-economic conditions. This obscured possible glaring correlations between HQI and vegetation cover. Furthermore, the traditional land tenure system administered in Kumasi which allows both wealthy and poor native Asantes to acquire land at fairly low "drink money" values under the auspices of the Asantehene (the king of the Asante kingdom) and his sub-chiefs (Devas and Korboe 2000) and to live together in the same neighborhood and submetropolis prevents the creation of distinct constellations of under privileged submetropolises in the city. Nevertheless the wide variation in per capita UGS among submetropolises is tantamount to environmental injustice. As explained previously, this pattern of UGS distribution could be an artefact of the history of urbanization in the city: hitherto the traditional old towns (submetropolises) such as Tafo, Suame, Menhyia, Subin and Bantama have the lowest per capita UGS area. Due to the influence of past imperialism, better environmental education and awareness, government residential and rapidly developing peri-urban areas have assumed a greener outlook. A thorough investigation of UGS distribution at the neighborhood level in Kumasi may reveal more compelling evidence of distributive injustices and is strongly recommended.

Conveyed in the UGS and tree cover Gini coefficient of 0.26 is the implication that vegetation is somewhat evenly distributed among the inhabitants of Kumasi. However, closely matching vegetation to inhabitants does not necessarily mean access or utilization of these green spaces. Indeed, only a few privileged households/individuals or interest groups or parties actually own, access, and exploit the green spaces of Kumasi. There are many others who see green but hardly benefit directly from it besides the inherent intrinsic and public goods and services these green spaces provide.

The results further reveal that fewer public green spaces than originally intended currently exist in Kumasi, fomenting doubts as to whether Kumasi is still the "Garden city" of West Africa. With several home gardens, vegetation on institutional compounds, and a network of grasslands and farmlands along water flow paths, the jurisdictional area of KMA is 33 % green albeit at risk of being completely greyed out due to pressure from built-up expansion. Strict adherence to urban plans, policies (e.g. Water Resources Commission advocated 100 m no development zone around waterbodies policy) and actions restraining neglect, destruction and unguided conversion of green spaces are required to revert the status quo. The current green cover can persist and even expand if 1) bare areas in the city are converted into some green cover: lawns or plantations; 2) trees are planted along all major and minor roads in the city; 3) best management practices geared at greening and protecting wetlands and other sensitive landscapes in the city are instituted; 4) UGS are given a facelift and turned into attractive spaces for tourism, recreation etc. and 5) halt all form of non-green activities in such buffers including waste disposal, mechanical/fitting shops, buildings, etc., and prohibition of open defecation. Green spaces could be artistically planted with adequate trees and beautiful lawns and maintained for recreational purposes which could lead to the creation of a useful blue-green corridor connecting nature in the city to the rural areas.

It is important to reiterate that green cover is an indicator of the city's resilience to climate change (Lindley et al. 2015). Green spaces minimize surface runoff and floods by providing conduits for accelerated runoff water from the paved surfaces in the city. Through evaporative cooling and shading urban vegetation directly regulate temperatures, hence mitigate heat island effects and reduce cost of cooling homes. Carbon storage benefits to partially compensate for the vast amount of CO_2 released into the atmosphere via urban energy consumption are discussed in the next chapter whilst biodiversity, the basis for all ecosystem services supplied by green spaces is discussed in chapter 5. Food, fiber, fuelwood, air purification, supply of supporting and cultural services for the wellbeing of urbanites are at the domain of UGS.

3.5 Conclusion

Availability and equitable distribution of vegetation in cities is essential to advancing the course of sustainable development. However, the extent, composition and basis of distribution of green spaces in cities in developing countries is fraught with uncertainties. This chapter discussed the temporal and spatial changes in green cover, major green space types, and the possible distributive injustices pertaining to green spaces in Kumasi. Multi-resolution image analysis provides a worthwhile means to monitor land cover dynamics in cities: about 44 % loss in green cover in Kumasi since 1986, with the rate of loss in the most recent five years (2009-2014) being far greater than any period before. Severe vegetation losses due built-up expansion are to some extent partially compensated for by some vegetation recovery in the core urban area attributable to greater awareness and concern for environmental issues in the city. Sprawl accentuates natural resource consumption and feedbacks positively on climate and urban life.

At the current pace of vegetation loss, there is high likelihood of further compromising Kumasi's current 33 % green cover. Home gardens and vegetation on institutional compounds being the dominant green space types sustaining the bulk of this green cover, underlines the importance of private individuals and traditional leaders in spearheading the greening of the city. The caveat however is that home gardens and land under the jurisdiction of traditional leaders are driven by economic motives and at severe risk of being converted to build up areas as and when land values rise. The local government, KMA, however, needs to be proactive to revamp greening of the city for the common good of the inhabitants and in accord with the targets of SDG 11. In this regard, reclaiming and rejuvenating bare, deplorable, encroached, and usurped public parks should be a major priority.

While no explicit socioeconomic evidence accounts for distribution of green spaces in the city at the submetropolis level, there is nuance evidence of distributive injustices in terms of uneven amounts of per capita UGS among submetropolises, subtle inequalities in UGS distribution among populace and limited availability of public spaces for common access of all inhabitants. Further investigations of this subject at the finer scale of neighborhood may provide more explicit answers and is suggested. Given the pace of urbanization and changes in life styles of urbanites, the need for public spaces for the aged and particularly for children and the youth cannot be overemphasized. Establishing public green spaces as well as greening streets and bare areas in parts of the city where per capita green space is low is extremely necessary. These findings are essential for local government and urban planners to better manage the land and plan for green infrastructure networks in the city. For the sustainability of Kumasi, green space conservation and management plans are required. It is also imperative to innovatively reconstruct the urban planning institutions to integrate multiple disciplines such as ecology and aspects of the social and physical environment into its folds. Failure to heed this latter suggestion could lead to path dependency (Matthews, Lo, and Byrne 2015). Furthermore, research on monitoring urban land use change and addressing environmental injustices, institutional motivators of urban greening and intrinsic and extrinsic values of green spaces at the neighborhood level are encouraged. Institutional, social, and economic evaluation of the human actions and green space availability and relevance are long overdue. Future research should also focus on use of higher resolution satellite images in mapping and monitoring green cover changes, urban vulnerability to disasters and health implications of green spaces especially in relation to short-lived climate pollutants (SLCPs) in African cities.

4 BELOW AND ABOVEGROUND CARBON STORAGE IN KUMASI, GHANA: DOES GREEN SPACE TYPE MATTER?

4.1 Introduction

Urbanization and climate change are coupled contemporary global processes that interact on the earth surface with feedback effects on each other and are predicted to escalate with time (UN-Habitat 2011). Africa, the most vulnerable and fastest urbanizing continent in the world with urban population growth rate of 1.1 % per annum, is expected to further urbanize by 16 percentage points by 2050 (United Nations 2014). Nearly 90 % of African cities are exposed to and affected by at least one form of natural disaster, i.e. desertification, cyclones, extreme heat, floods, volcanic eruptions, drought, air pollution, etc. (Di Ruocco et al. 2015). Climate change is projected to aggravate these disasters and further endanger the lives of urbanites. Moreover, cities globally, account for 70 – 80 % of CO_2 emissions into the atmosphere including other greenhouse gases (GHG) (OECD 2014; UN-Habitat 2011). Carbon dioxide, in conjunction with bare surfaces resulting from urbanization create 'heat islands' and severe air pollution (Lindén 2011; Hardy and Nel 2015; Bowler et al. 2010; Peng et al. 2012), causing discomfort to the living and sometimes fatalities. Although additional conurbation expansion in the developing world, further convolutes these climate-related challenges, it presents opportunities to innovatively create livable, carbon neutral, and environmentally benign cities.

Multiple alternatives exists that can address climate change and its effects in cities. The choice of a solution, depends on the political, social, economic conditions and resources available to design and implement an intervention. UGS constitute a low-cost local strategy that can easily be adopted and practiced in most human settlements at a limited scale and with limited institutional support. Although often obliterated by human demographic growth as a consequence of poor planning, it is clear from the literature that UGS of various forms remain a major part of the urban landscape of many cities in developing countries (Lindley et al. 2015). Urban green spaces, in addition to their numerous co-benefits, collapse slowly, are more resource-efficient and more resilient to stress induced by both urbanization and climate change processes compared to engineering solutions (European Commission 2015).

In cities in the Global North, UGS have been documented as important carbon sinks(Nowak 1993; Jo and McPherson 2001; Nowak and Crane 2002; Hutyra et al. 2011; Davies et al. 2011; Strohbach and Haase 2012; Nowak et al. 2013; Russo et al. 2014; Schreyer et al. 2014; Dorendorf et al. 2015). Defined as the relics of vegetation (i.e. parks, tree lots, cemeteries, home gardens, lawns, grass and farmlands, wetlands, and bare ground), sandwiched by grey infrastructure (buildings, roads and paved surfaces) in cities (Benedict and McMahon 2002; Breuste et al. 2013), UGS can sequester carbon in trees, other vegetation and soil. Carbon stocks and fluxes have been estimated from allometric equations, remote sensing, eddy covariance techniques, GHG inventory using emission factors and activity data and models (e.g. i-Tree) (Nowak and Crane 2002; Velasco et al. 2016; Zhang et al. 2012). Through photosynthesis, plants absorb CO_2 from the atmosphere, transmit it to the soil in the form of living (roots) and dead organic matter (humus) and release it back to the atmosphere during respiration. Human management of UGS can alter these source/sink processes with the climate and hence the ecosystem services they provide (Davies et al. 2011; Francis 2013). Because urbanization patterns differ markedly at the global and regional scales governed by varying political, social and economic drivers, it will be a misestimate to extrapolate carbon stocks measurements in cities in other regions to cities in Africa.

Besides influencing the local and regional climates, carbon cycle, and energy budgets (Lal 2012), UGS are preserves of several ecosystem services. These include direct mitigation of urban heat island effect by cooling through evapotranspiration and shading, improving air quality (regulating particulate matter, NOx, SO_2, CO and O_3) (Brack 2002; Nowak et al. 2006; Chaparro 2009; Jim and Chen 2009), mitigating floods and runoff (Van Leeuwen and Koomen 2012), recreation and cultural services supply, erosion control (Heinze 2011; Bolund and Hunhammer 1999), solid waste and sewage disposal, fuel and food provisioning, ground water supply (Vollmer and Grêt-Regamey 2013), acting as windbreaks, psychological and other health benefits (Tzoulas et al. 2007). The capacity of UGS to provide ecosystem services is reinforced by their area extent in the city, composition and biodiversity, and efficiency in their management.

Despite their worth, UGS remain marginalized in many national and regional carbon budgets. In Ghana and indeed throughout Africa, carbon stocks of cities are assumed to be zero (Henry et al. 2011). Where cities have been studied, carbon stocks estimates are based on low resolution satellite images (Asare 2009), which tend to severely underestimate carbon stocks (Raciti et al. 2012; Davies et al. 2013). Furthermore, the variation of carbon stocks among different green space types within the city matrix remains largely nebulous (Edmondson et al. 2014). Besides, carbon storage in both soils and vegetation differ strongly among cities (Pouyat et al. 2006; Nowak et al. 2013) because of varying socioeconomic, geographical, and biophysical peculiarities.

The goal of this chapter was to quantify and map the distribution of vegetation, soil and ecosystem carbon storage in Kumasi, Ghana. More specifically, the variability in carbon storage among UGS types and along urban zones was estimated. It was hypothesized that vegetation carbon densities and stocks in Kumasi are sensitive to green space type and urban zone.

4.2 Materials and methods

4.2.1 Study area

Kumasi metropolis is located in south central Ghana (6° 41"N, 1° 37"W, Figure 3.1). The climate is tropical, characterized by a bi-modal rainfall system: the major raining season being April to June and the minor season September and October. Mean annual rainfall and temperature are respectively, 1250 mm (Owusu 2009) and 26.4°C (Manu et al. 2006). Kumasi is sited in the moist semi-deciduous South-East Ecological Zone of Ghana with Ceiba, Triplochiton, Celtis and some exotic species being among the most common tree genera (KMA 2013). Soils are mainly forest ochrosols comprising of four main associations: *Bekwai-Nzima/Oda compound association, Kumasi-Asuansi/Nta-Ofin association, Akomadan-Bekwai Association, and Bomso-Nta-Ofin Compound association (largest in area extent) developed over Cape Coast granites and lower Birrimian phyillites* (Adu, 1988). The FAO World Reference Base (WRB) classifies the soil in Kumasi into two types: Haphic Alisols and Lithic Leptosols in the northern and southern halves of the city, respectively (European Commission 2013).

Kumasi has a land area of 254 km^2 inhabited by about 2.5 million people at a population density of 8,000 persons per km^2 and a growth rate of 4.8 % (Ghana Statistical Service 2012; KMA 2013). It hosts the largest open market in West Africa and is a central transiting point for travelers from within and beyond Ghana (Adarkwa 2011).

4.2.2 Vegetation sampling and aboveground carbon estimation

A stratified random sampling design (Nowak et al., 2008) was used to study carbon stocks in green spaces of Kumasi between July and December 2014. The stratification ensures that homogeneous units which capture key subgroups and minority groups of tree communities are created and hence improve precision of the survey (Levy and Lemeshow, 2008). Based on mean normalized difference vegetation index (NDVI), the city was partitioned into two strata: High Density Urban Zone (HDUZ or core urban; mean NDVI ≤ 0.11) and Low Density Urban Zone (LDUZ or peri-urban; mean NDVI > 0.11) (Figure 4.1A). The HDUZ stratum consisted of at least four sub-metropolitan areas: Subin, Tafo, Suame, Menhyia, Asukwa and fractions of the areas of Oforikrom, Bantama, and Asawasi (Figure 4.1A). The approximate green area of the HDUZ stratum is 430 ha. The LDUZ stratum spanned the areas Kwadaso, Nhyieaso, ¾ of each of Oforikrom and Bantama, fractions of Asawasi submetropolitan areas and included 2 km buffer off the Kumasi metropolitan assembly (KMA) jurisdictional boundary (Figures 4.1 and 3.5). The buffer captures the variation due to forest, agricultural and land use changes in the peri-urban area (which should serve as link between the hinterland and the city) of Kumasi. Estimated green cover in this stratum is about 1,250 ha.

The NDVI map was classified into eight UGS types including other land uses using ErdasImagine® (Figure 1B). Green spaces types were extracted by the visual interpretation method and classified based on vegetation structure, composition, location, function, and management (Figure 4.1B). These UGS include: 1) plantations, planted co-existing trees of at least 0.5 ha area and at least 80 % tree cover, managed or not; 2) natural forest, remnant clusters of naturally occurring native and endemic tree species of the tropical high forest of Africa of at least 0.5 ha with trees at least 5 m tall; 3) home gardens, trees-only, crops-only, tree-crop mixtures, and lawns growing within or adjacent residential housing compounds; 4) institutional compounds, vegetation - mostly trees growing within or as live fences around compounds of institutions, such as schools, hospitals, office buildings, etc.; 5) farmlands, farming areas, mostly peri-urban and adjacent to wetlands; 6) cemeteries/sacred grooves, vegetation, mainly trees on cemeteries; 8) public parks, e.g. zoo, golf course, botanical gardens; and 9) grasslands and rangelands (consist of 3 layers in Figure 4.1B: grass_wetlands, grass_uplands, and grass_lawns/lowlands), mostly along water bodies, may or may not be grazed (Appendix 3).

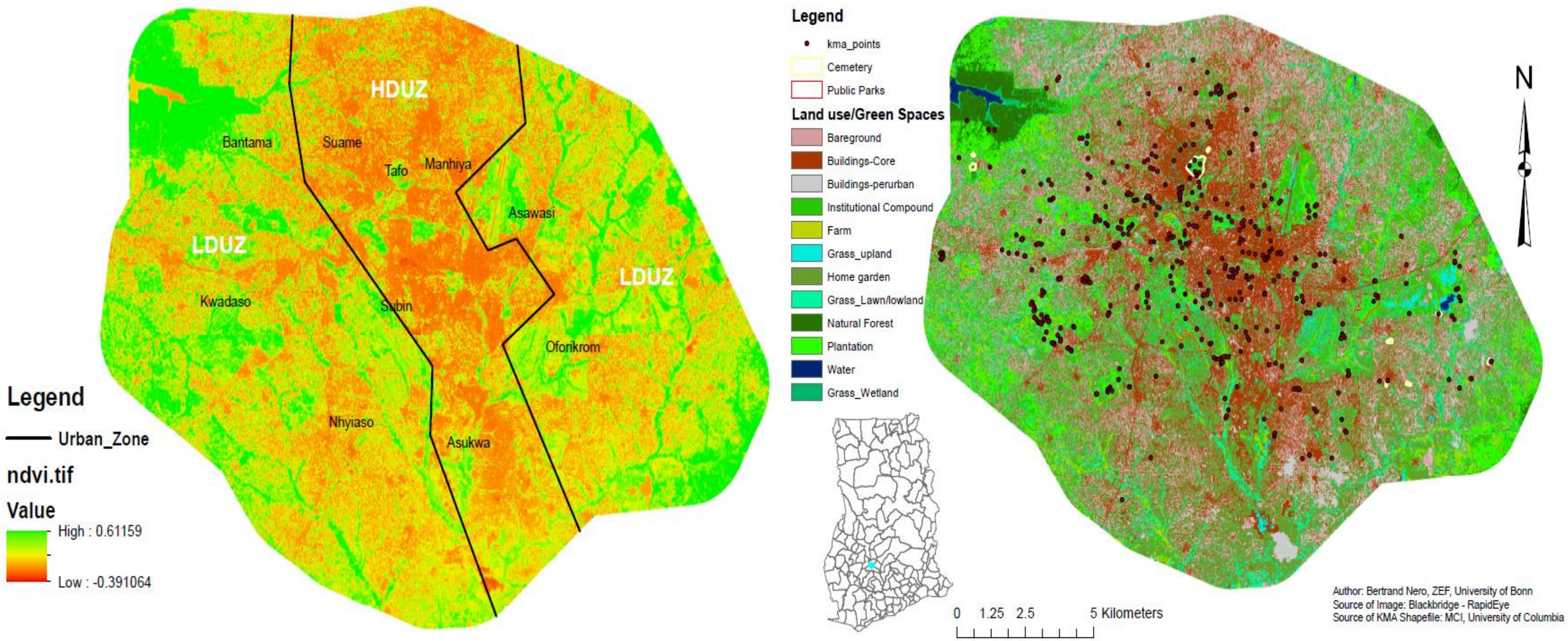


Figure 4.1 (A) Normalized difference vegetation index (NDVI) map; (B) distribution of green spaces and survey plots in Kumasi. Area between the two dark lines in (A) indicate the High Density Urban Zone (HDUZ), mean NDVI <0.11: outside these lines constitute the Low Density Urban Zone (LDUZ), mean NDVI > 0.11.

Producer's and user's accuracies for the different green spaces as well as non-green spaces (Figure 4.1B) were calculated. The producer's accuracy is the probability that a particular land cover on the ground was correctly classified as such (omission error). The user's accuracy is the probability that a classified object on the map was really the same object in the real world (commission error). Nevertheless, errors due to rapid changes in landscape may amount to misclassification and should not be discounted. The overall accuracy of the classification was 62.3 % with a Kappa coefficient of 0.56. A detailed description of accuracy assessment of the green space map is presented in chapter 3.

Sampling points were randomly generated on the green space map of Kumasi (Figure 4.1B). Except for home gardens, 10 m x 10 m quadrats were centered on each sampling point on the ground with the help of a compass, a distance tape measure, and ranging poles. All trees with diameter at breast height (DBH =1.3 m from ground) greater than 5 cm within the plot were counted by species and subsequently heights and DBH of each tree measured with a clinometer and diameter tape, respectively. In addition, the canopy cover and proportion of the plot covered by grass, crops, bare ground (or hard surface), small trees and shrubs (DBH = 1 – 5 cm), and buildings were determined. In plots containing herbaceous vegetation, cereals, and vegetables as well as on open grasslands 1 m x 1m quadrats were randomly established, the vegetation within was clipped to ground level and conveyed to the laboratory for oven drying.

In each stratum (zone), sampling intensity depended on the type of UGS, the extent of vegetation cover, size of trees, composition and diversity of species (Table 4.1). For instance, in the HDUZ stratum, home gardens and trees on institutional compounds, which constituted more than half the green space cover, were the most sampled (196 plots). However, home gardens can be as varied as a single tree in a house yard to as large and complex as an acre (436 m^2) of several large and small tree species mixed with perennial and annual crops. Overall, 273 and 181 sample plots were surveyed in the HDUZ and LDUZ, respectively.

On large farmlands containing staple food crops such as *Musa* spp., *Manihot* spp., and *Colocasia* spp., 25 x 25 m plots were established on sample points and the number of individuals per species counted. Fifteen individual plantain crops of varying sizes were destructively sampled (clipped at ground level, fruits excluded) and conveyed to the laboratory for determination of dry weights and carbon.

Table 4.1 Number of plots and post stratification survey weights applied in surveying and estimating organic carbon parameters of the different green space types in two strata in Kumasi.

Stratum[1]	Green space type	Number of plots	UGS Area (ha)	Sample Area (m^2)	Weight
HDUZ	Plantation	17	114	1,700	0.86
HDUZ	Home garden	118	1,715	91,403	0.67
HDUZ	Institutional compounds	76	664	36,065	0.24
HDUZ	Farmlands	16	210	1,300	0.24
HDUZ	Cemeteries	32	30	3,200	2.09
HDUZ	Public parks	18	80	2,300	0.12
HDUZ	Grass/range lands	9	575	1,000	7.44
LDUZ	Plantation	38	1,031	3,800	3.51
LDUZ	Natural forest	5	591	910	8.40
LDUZ	Home garden	36	6,391	25,907	3.19
LDUZ	Institutional compounds	36	2,476	17,496	1.83
LDUZ	Farmlands	15	1,254	4,263	3.80
LDUZ	Cemeteries	8	11	30,697	0.01
LDUZ	Public parks	34	111	6,100	0.24
LDUZ	Grass/range lands	9	2,333	1,100	4.88

[1] Strata consist of High Density Urban Zone (HDUZ) and Low Density Urban Zone (LDUZ). Weight is the ratio of the proportion of the area a specificied UGS type relative to total green area of the city to the proportion of the sample area of this same UGS type relative to total sample green area used in the study.

In home gardens, a complete inventory of tree and crop species was conducted for the entire garden. Areas of gardens were calculated using remote sensing aided by google earth imagery and ground-truth data. Whenever sampling points fell on institutional, private or cultural heritage sites, permission was obtained from the appropriate authorities. If permission was not granted, a new sample was randomly selected within the same neighborhood.

4.2.3 Aboveground carbon estimation

Biomass for each sampled tree was calculated using allometric equations derived from literature (Table 4.2). These equations are established physiological relationships between DBH, height, wood density (or specific gravity) and sometimes volume and vary between species, within species and among guild types due to site conditions (Henry et al. 2010; Henry et al. 2011). Several studies have suggested the use of species-specific equations where available for same species; else equations for same genus, family, and site (or species group) should be used (Nowak 1993; Nowak and Crane 2002; Strohbach and Haase 2012). Where no species specific equations existed, generalized equations developed specifically for pan-tropical forest (Chave et al. 2005; Chave et al. 2014) and validated by biomass estimation studies in tropical high forest in Cameroon (Fayolle et al. 2013) were used. Equation 4.1A was used where tree height was available, otherwise eq. 4.1B where only DBH was available. Kumasi is located within the moist forest zone of Ghana, hence the adoption of equation 4.1. For plants of the Arecaceae family, biomass was estimated using equation 4.2 (Khalid et al. 1999). The biomass for bamboo culms was estimated following Nath et al. (2009) allometric model for *Bambusa vulgaris* (eq. 4.3). Citrus trees have small stems and branch profusely below the 1.3 m mark on the stem. Hence, their biomass was estimated using equation 4.4 (Schroth et al. 2002). Species-specific wood densities were obtained from local and global databases (FAO 1997; Orwa et al. 2009) and unpublished literature (Adu-Bredu, personal communication 2015). For species without readily available wood specific gravities, family averages were used as surrogates. For doubtful or unknown species, average wood specific gravities at the stand level were used. Below ground biomass (BGB) was calculated using equation 4.5 (Cairns et al. 1997).

Table 4.2 Allometric equations used for the estimation of biomass in this study

Source	Allometric equation	R^2	Eq.
Chave et al. (2014)	$AGB = 0.0673 \times (\rho D^2 H)^{0.976}$	RSE = 0.357	(4.1A) or
Chave et al. (2005)	$AGB = \rho * \exp[-1.562 + 2.148*\ln(D) + 0.207*\ln(D)^2 – 0.0281*\ln(D)^3]$	$R^2 = 0.996$	(4.1B)
Khalid et al. (1999)	$AGB = (725 + 197H)*0.27$	$R^2 = 0.922$	(4.2)
Nath et al. (2009)	$\log(AGB) = 2.281 + 2.149*\text{Log}(D)$	$R^2 = 0.956$	(4.3)
Schroth et al. (2002)	$AGB = -6.64 + 0.279BA + 0.000514BA^2$	$R^2 = 0.94$	(4.4)
Cairns et al. (1997)	$BGB = \exp(-1.0587 + 0.8836*\ln(AGB))$	$R^2 = 0.83$	(4.5)

Where ρ is species-specific wood density (g/cm^3) or specific gravity, ln = natural logarithm, exp = inverse of natural logarithm, D is the diameter at breast height (at 1.3m aboveground level) in cm, H is the total height of the tree in m, AGB is the aboveground biomass of the tree in kg, BA = ground level basal area in cm^2, BGB = belowground biomass in kg, RSE = root-mean-square error, and log = logarithm to base 10.

The total tree biomass was converted to carbon using a conversion factor of 0.474 (Range: 0.419 -0.516) (Martin and Thomas, 2011). Tree carbon stock (tC) for each UGS type was estimated as a product of the mean carbon storage (t C/ha) for the given UGS type (i) and the area coverage of the same UGS type (i), adjusting for tree cover. The total number of trees for each UGS type was estimated using a similar approach as above. Carbon storage, basal area (BA), and tree population density were estimated as the plot total (carbon, number of trees, BA) divided by the area of the plot.

Dry weights of crops, herbs and grasses were determined after oven drying at 68°C for 72 hours. However, dry weights of some food crops e.g. *Manihot* spp., *Colocasia* spp., *Dioscorea* spp., were obtained from the literature. Herbaceous biomass was converted to carbon stocks using a conversion factor of 0.45 (Piao et al., 2007). Because crops and herbaceous plants grow under trees, their area coverage exceeds the area coverage derived from aerial images. Hence, area cover for herbs and crops was adjusted to account for plants growing under trees. The total carbon stock for the crops and herbaceous plants was determined as a product of the mean UGS vegetation carbon density and the respective UGS area.

4.2.4 Soil sampling and carbon measurements

About 480 soil samples from 161 profiles were collected within August – December 2014. Samples were randomly drawn from all eight UGS types in each stratum as described previously. Each profile was cored to a depth of 60 cm (0-15 cm, 15-30 cm, 30-60 cm) using a regular soil auger and a bulk density soil sampling ring, each with 53 mm diameter (Eijkelkamp Agrisearch Equipment, Netherlands). The undisturbed soil collected in cylinders down each profile (partitioned into the three layers or depth segments) was conveyed to the laboratory for bulk density determination.

Bulk density samples were dried at 105°C, weighed and the density determined as the dry weight per unit volume of cylinder. Samples for chemical analysis were dried at 68°C, grinded and sieved through a 2 mm mesh to remove large pebbles and stones. Coarse roots were removed by hand. The particles > 2 mm weighed less than 5 % of the total weight of each soil sample. The sieved sample was analyzed for C and pH. The Walkley-Black technique was used for carbon analysis. Soil organic carbon (SOC) content was calculated without a recovery factor. Since soil organic matter (SOM) contains 58 % organic carbon, % SOM is estimated by multiplying % SOC concentration by a factor of 1.724.

4.2.5 Statistical analysis

Statistical analyses were conducted using SAS (version 9.3, SAS Institute Inc 2013). Differences in carbon densities, BA, and number of trees in the different UGS types and urban zones were assessed using SURVEYREG procedure in SAS. SUVEYREG takes into account stratification and complex design information together with the auxiliary information about independent variables and improves the precision of the estimates compared to other procedures such as GLM, ANOVA, and mixed models (SAS Institute Inc., 2008). It fits linear models for survey data and computes regression co-efficients and their variance-covariance matrices as well as provides test of significance for model effects and for specified estimable linear functions of the model parameters (SAS Institute Inc. 2008). Post stratification survey weights were applied to reduce biases in the estimators and variances arising from several sources (Table 4.1). Weights were computed as ratios of the proportion of the area of a specified green space type at a citywide scale to the proportion of the sample area of this same green space type relative to the total area of green spaces sampled in the study. Weightings were necessary to minimize the effects of errors due to noncoverage and erroneous inclusions (Levy and Lemeshow 2008). Statistically significant differences were tested at alpha =0.05. Erdas Imagine®2015 and ArcGIS ArcGIS (version 10.1, ESRI) were combined to generate the green space (Figure 4.1) and carbon stock maps.

4.3 Results

4.3.1 Vegetation carbon

A total of 3,527 stems belonging to 2,755 trees were recorded in Kumasi. At least 162 species belonging to 42 families were correctly identified. Sixteen species could not be identified to the species nor genus level because they were either dead or in a form without conspicuous phenological features. Thirty plots had no trees. The largest tree was a Kapok tree (*Ceiba pentandra* (L.) Gaertn) with a diameter of 272 cm, located in a plantation. Among UGS types, mean DBH was significantly different ($p<0.0001$). With 61.8 cm, trees on institutional compounds had the highest mean DBH while plantation, home garden, farmlands, and grasslands were not significantly different among them with mean DBH of 32±4.2 cm, 33.6±2.1 cm, 44.3±8.3 cm and

39.9±8.8 cm, respectively. The overall site mean trees density was 377 trees/ha (95 % CI = 335 – 419) with pocket plantations having the highest mean tree density of 800 trees/ha (95 % CI = 619 – 981) (Table 4.3). Dead trees, deadwood, and trees with DBH < 5 cm and forest undergrowth trees, common only in the few secondary natural forest in this city, were excluded in the survey.

About 55 % of the study area (KMA area+2km buffer) is covered by UGS (Table 4.3; Figure 4.1). Home gardens and institutional compound constitute 46 % and 18 % of the UGS cover of Kumasi, respectively (Table 3.4). Plantations, natural forest, public parks, grasslands and farmlands account for 7, 3, 1, 17, and 8 % of green area, respectively. The green cover is 40 % in the HDUZ area and 60 % in the LDUZ area. Tree cover constitutes 61 % of the entire green area of Kumasi.

A total of 2,180,845 ± 26,617 t C is stored within vegetation across Kumasi metropolis (Table 4.3; Figure 4.2), equivalent to 211.28 ± 18 t C/ha for UGS within the study area (and 111 ± 7.0 t C/ha for the entire metropolitan area covered in this study. More than 99 % (2,175,759 ± 26,614 t C) of this total carbon is stored in trees, out of which 12 % is stored in the roots. Green spaces that stored the most vegetation carbon included plantations (15 %), natural forest (19 %), home gardens (23 %), and institutional compounds (35 %). Green spaces with the least carbon stocks were public parks, farmlands, grasslands, and cemeteries, which respectively stored 3.4, 3.5, 0.8 and 0.4 % of the total vegetation carbon. Crops and herbaceous vegetation combined stored about 5,086 ± 2.5 t C citywide (Table 4.3). The HDUZ area stored about 11 % of the total carbon estimated in the city (Table 4.3; Figure 4.2).

Carbon stored in trees is significantly different ($p = 0.0088$) for aboveground carbon (AGC) and for belowground carbon (BGC) ($p = 0.0097$) among the UGS types in the two urban zones. Except for farmlands where tree carbon storage in the HDUZ is almost twice that of the LDUZ area, carbon storage in all other UGS types in LDUZ exceed that of the HDUZ. Comparison of means of the different green spaces are shown in Table 4.3. Natural forest had the highest AGC storage of 618 t C/ha (95 % CI = -163 – 1399) while that of public parks, cemeteries, trees on institutional compounds, and plantations are not significantly different (Table 4.3) and are respectively: 420 (95 % CI = 275 – 564), 291 (95 % CI = 165 – 417), 228 (95 % CI = 179 – 277) and 256 t C/ha (95 % CI = 132 – 378).

Table 4.3 Means (Standard errors) carbon stored in trees aboveground (AGC, t C/ha) and belowground (BGC, t C/ha), crops/herbs (t C/ha); basal area (BA); tree population density; land area; and percent tree cover for the different green space types in the two urban zones of Kumasi. Numbers in the same column within the same stratum followed by the same small letter are not significantly different among UGS types. Numbers in the same UGS type followed by different capital letters are significantly different among strata (alpha =0.05).

Stratum[2]	UGS	AGC (t C/ha)	BGC (t C/ha)	Crop/Herb C (t C/ha)	BA (m^2/ha)	Tree Density (no./ha)	Land Area (ha)	Tree Cover (%)	Number of trees	Total Carbon Stock (t)
HDUZ	Plantation	130 (14)cA	22 (2)cB	-	30.8 (63)bB	659 (110)	114	96 (4)	64,518 (453)	16,479 (66)
HDUZ	Home garden	58 (7)d	9 (0)d	1.3 (0.25)	21.7 (23)b	240 (16)	1,715	61 (3)	249,062 (695)	70,726 (326)
HDUZ	Institional	187 (25)ab	27(3)ab	-	60.6 (73)a	343 (31)	664	80 (2)	181,687 (447)	113,089 (405)
HDUZ	Farmland	143 (34)bc	20 (4)bc	2.1 (0.66)	48.6 (147)ab	268 (42)	210	53 (5)	29,657 (466)	18,255 (423)
HDUZ	Cemetery	292 (53)a	38 (6)a	3.2 (0.00)	94.5 (177)a	228 (21)	30	69 (5)	4,813 (29)	6,999 (83)
HDUZ	Public park	178 (52)abcB	29 (7)abcB	-	60.7 (148)ab	625 (80)	80	99 (1)	49,534 (32)	16,409 (24)
HDUZ	Grassland	27 (00)e	5 (0.0)e	0.04 (6×10^{-2})	13.1 (0.0)cB	200 (00)	575	10 (9)	5,504 (00)	861 (0.0)
LDUZ	Plantation	284 (76)abA	39 (8)abA	-	72.8 (194)aA	863 (119)	1,031	98 (1)	876,306 (1,593)	316,911 (1132)
LDUZ	Natural forest	618 (397)ab	73 (43)ab	-	100.5 (602)ab	296 (78)	591	100 (0)	175,054 (00)	408,326 (0.00)
LDUZ	Home garden	93 (33)c	13.38 (4.11)c	1.4 (0.44)	26.3 (71)b	241 (36)	6,391	63 (5)	970,762 (11,074)	432,535 (11,449)
LDUZ	Institutional	274 (44)b	36.5 (5.06)b	-	82.8 (112)a	298 (38)	2,476	84 (3)	618,734 (2,823)	643,488 (3,664)
LDUZ	Farmland	77 (20)c	10.56 (2.34)c	0.94 (0.55)	28.6 (71)b	140 (30)	1,254	54 (8)	94,672 (2,924)	59390 (2,135)
LDUZ	Cemetery	290 (163)ab	38.4 (20.5)ab	1.09 (0.59)	62.1 (300)ab	327 (112)	11	65 (8)	2,317 (91)	2,332 (150)
LDUZ	Public park	485 (91)aA	61.7 (9.87)aA	-	91.5 (145)a	446 (55)	111	99 (1)	49,026 (30)	57,612 (57)
LDUZ	Grassland	46 (8)c	7.4 (1.32)c	0.048 (1×10^{-1})	26.1 (0.31)bA	200 (71)	2,333	40 (12)	65,592 (6,869)	17,432 (930)
	Mean	211 (18)	28.79 (2.0)	10.2 (2.5)	56.1 (38)	377 (38)	1,172	71 (4)		
	p-value	**0.0088**	**0.0097**	**0.0025**	0.1178	0.1197		**0.0097**		
	Total					17,586			3,564,277 (27,884)	2,180,845 (20,843)

[1]UGS = Urban green space type, [2]Stratum (zone) include; high density urban zone (HDUZ), low density urban zone (LDUZ)

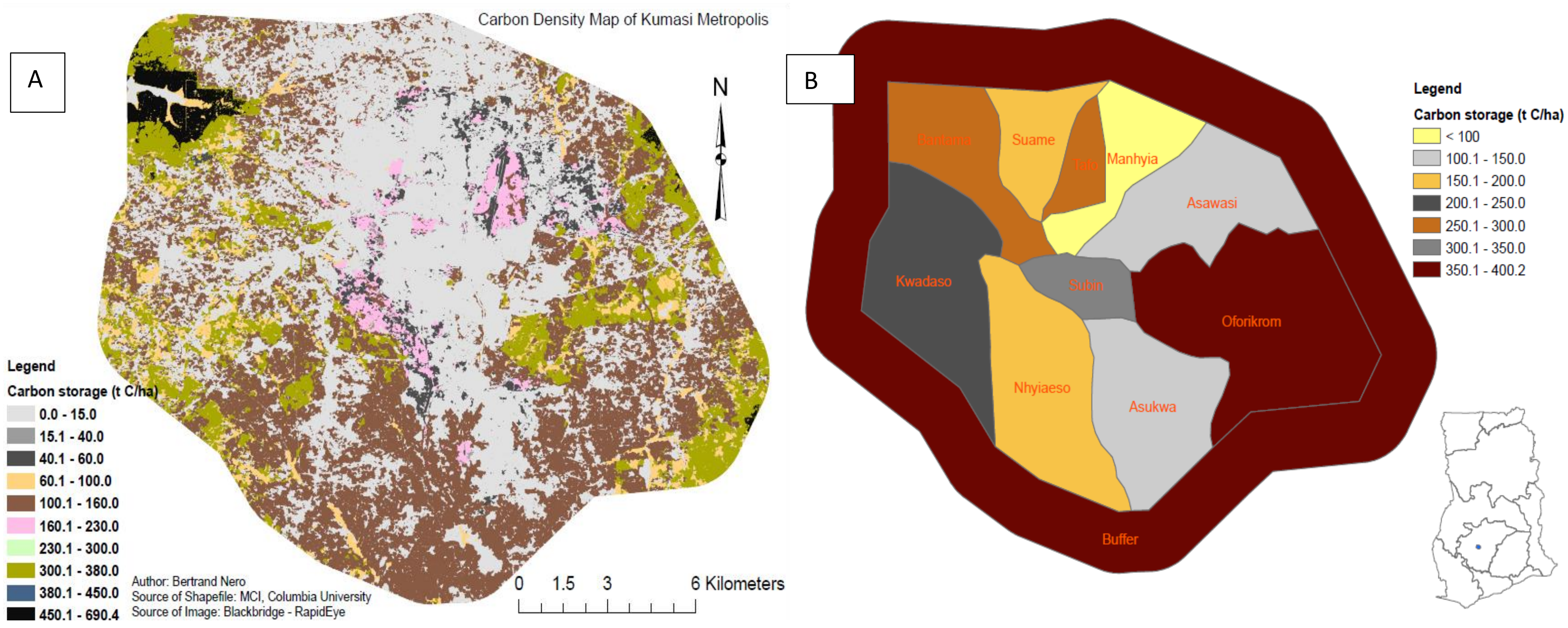


Figure 4.2 Aboveground tree carbon storage (A) and submetropolis-level aboveground tree carbon storage (B) distribution map of Kumasi metropolitan area.

Although significantly lower than the aforementioned green spaces, AGC storage in farmlands and home gardens are not significantly different, respectively storing 94 (95 % CI = 60 – 129) and 71 t C/ha (95 % CI = 45 – 97). AGC storage in grasslands was significantly lower than all other UGS types in the metropolis with a mean of 41.9 t C/ha (95 % CI = 27 – 57). Differences in mean BGC carbon densities are similar to the patterns observed in AGC (Figure 4.2A, Table 4.3).

Carbon storage for crops on farmlands and home gardens are significantly greater than C stored in grasslands (Table 4.3; $p<0.0001$) though C storage in crops and grasslands were just incommensurable to C storage in tree dominated green spaces. Mean crop carbon storage are 1.4 t C/ha (95 % CI = 0.9 – 1.9) and 1.5 t C/ha (95 % CI = 0.5 – 2.2) for home gardens and farmlands, respectively. Grassland has a carbon storage of 0.00045 t C/ha (Table 4.3).

Carbon storage in live vegetation increased from the middle of the city to the periurban fringes (Figure 4.2A). Vegetation carbon storage range from 0 t C/ha in built-up areas, bare ground and roads to 690 t C/ha in the relics of natural forests found in the periurban fringes in riparian areas e.g. the Owabi Wildlife sanctuary behind Bantama (Figure 4.2). Submetropolitan UGS carbon storage also vary widely across the city (Figure 4.2B). Oforikrom stores the highest carbon (~380 t C/ha) and Menhyia has the least (<100 t C/ha). The 2 km buffer around the political boundary of Kumasi metropolis stored slightly more carbon (400 t C/ha) than any submetropolis in the city. Carbon accumulated mostly in the west and east parts of the city, the area designated as LDUZ. The HDUZ holds little carbon due to high build-up density. Mean above ground and belowground tree carbon storage in the LDUZ are statistically greater ($p= 0.0121$ and $p=0.0115$, respectively) than in the HDUZ. Tree size (basal area) per stand explained 83 % of the variation in stand biomass.

4.3.2 Soil carbon

Urban green space type and soil depth interaction effect significantly affect SOC storage ($p<0.0001$), reflecting a general decline in soil carbon storage with depth (0-15 cm = 29.4 ± 2.5 t C/ha; 15-30 cm = 23.4 ± 1.2 t C/ha; 30-60 cm = 34 ± 2.65 t C/ha, n = 161). In the A (0-15 cm) soil depth, cemeteries and plantations hold the highest SOC. Except for natural forests which hold the least SOC in all depths, the other UGS types do not differ significantly in the top layer. Similar patterns are observed in the 15-30 cm depth, where cemeteries hold the highest SOC and in the 30 – 60 cm depth where home gardens and institutional compounds have the highest SOC. Public parks and natural forest store the lowest SOC in the B (15-30 cm) and C (30-60 cm) soil depth segments, respectively. Within each UGS type: institutional compound, cemeteries, farmlands, public parks, and grasslands, differences in SOC storage between depth segments were not significant. In home gardens and natural forest, SOC were statistically highest in the 30–60 cm soil depth (Table 4.3).

Citywide total SOC stocks to the 60 cm depth was 1 577 ± 245.7 Gg C (1Gg = 1000 t). This gives a mean profile SOC storage of 81.1 ± 1.3 t C/ha in the entire UGS cover of the metropolis. The distribution of carbon in the profile is correspondingly 30, 27, and 43 % in the 0-15, 15-30, and 30–60 cm soil depths. Soil organic carbon storage to the 60 cm depth is proportional to aerial coverage of the green space type. For instance, home gardens, which occupy about half of the UGS cover of Kumasi (Table 4.2, Figure 3.5), store 54 % of the total topsoil organic carbon (Table 4.5).

Table 4.4 Mean soil organic carbon (SOC, t C/ha) partitioned among depths and within different green space types in Kumasi. Means (standard errors) within the same depth followed by the same small letter are not significantly different and means within each green space type (same row) followed by the same capital letter are not significantly different at alpha = 0.05.

UGS[1] type	Soil depth (0-15 cm)	(15 – 30 cm)	(30-60 cm)	(0-60cm)
	(t C/ha)			
Plantation	34.1 (8.2)abA	20.7 (1.9)bcB	27.7 (2.8)bcA	83.5 (12.7)b
Natural forest	7.7 (1.8)cB	20.6 (0.4)cA	17.2 (3.6)cA	45.5 (5.80)c
Home garden	30.8 (2.7)bB	28.7 (2.8)bB	45.5 (6.3)aA	105 (11.9)ab
Institutional compound	22.5 (5.5)bA	21.9 (3.4)bcA	42.2 (13.6)abA	86.6 (22.5)b
Farmlands	26.3 (3.6)bA	18.5 (3.0)cA	26.8 (4.4)bcA	71.5 (11.0)b
Cemeteries	43.9 (5.9)aA	42.7 (5.6)aA	24.1 (15.7)bcB	110.7 (27.2)a
Public parks	29.7 (8.4)bA	17.8 (5.2)cA	28 (9.4)abcA	75.5 (22.9)b
Grassland	23.6 (3.4)bA	20.5 (3.4)bcA	27.9 (6.0)bcA	71.9 (13.4)b
Mean	29.4 (2.5)	23.4 (1.3)	34 (2.7)	81.1 (15.9)

[1]UGS = urban green space, n = uneven (range between 5 and 20)

The distribution of SOC in the metropolis is presented in (Figure 4.4). Buildings, roads, water bodies, and bare ground were assumed to have zero soil C and conseqeuntly no samples were collected. As a result, the city center has low soil carbon which progressively increases towards the fringes (with high vegetation) (Figure 4.4). Areas with large vegetation cover hold large carbon stocks.

Table 4.5 Soil organic carbon storage (SOC in Gg; 1 Gg = 1,000 t) at three depth segments in several UGS types in Kumasi. Means are followed by standard errors in parentheses.

Green Space	(0-15)	(15 - 30)	(30-60)	(0-60)
Plantation	39.1 (9.3)	24.7 (2.1)	31.7 (3.2)	94.5 (14.7)
Natural forest	4.6 (1.1)	12.2 (0.2)	10.2 (2.1)	26.9 (3.4)
Home garden	249.9 (22.2)	232.7 (22.8)	368.6 (51.3)	851.2 (96.3)
Institutional compound	70.6 (17.3)	68.6 (10.8)	132.5 (42.6)	271.7 (70.7)
Farmlands	38.4 (5.3)	270.3 (4.3)	39.2(6.5)	104.7 (16.1)
Cemeteries	1.8 (0.2)	1.8 (0.2)	1.0 (0.6)	4.6 (1.1)
Public parks	5.7 (1.6)	3.4 (1.0)	5.3 (1.8)	14.4 (4.4)
Grassland	68.6 (9.8)	59.6 (11.6)	81.0 (17.2)	209.2 (39.0)
Total	478.7 (17.6)	429.0 (66.9)	669.6 (125.7)	1,577.2 (245.7)

N = 5 – 30 for UGS types, N = 161 for each depth and for entire study.

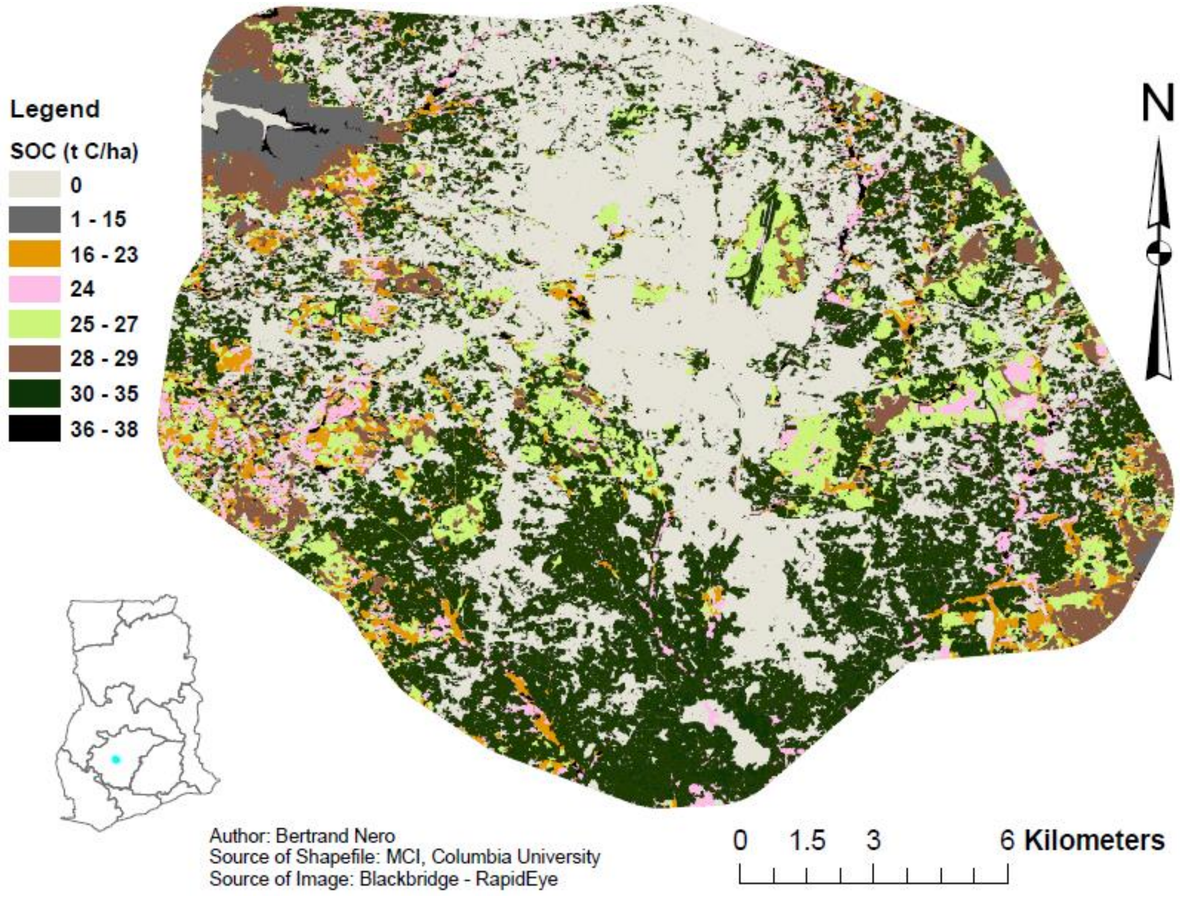


Figure 4.3 Soil organic carbon storage distribution map of Kumasi metropolis.

4.3.3 Total ecosystem carbon

Vegetation and soil carbon combined give an estimated total of 3758.1 ± 272.3 Gg C in the Kumasi metropolis: equivalent to 270 ± 22 t C/ha per UGS cover or 125.7 ± 8 t C/ha for the entire study area (Table 4.6). Incidentally below and aboveground carbon stocks are even: with 42 % in soil, 6 % in roots, and 51.5 % in aboveground shoot biomass. In grasslands, farmlands, and home gardens, at least 60 % of the total carbon is stored in soil whereas in tree dominated UGS (i.e. natural forests, plantations, and trees on institutional compounds) at least half of the total C is held in vegetation. Conversely, 36 % of the total city carbon is in home gardens while the tree dominated UGS, i.e. institutional compounds, plantations and natural forests, respectively, hold 27, 11 and 11 % of the total carbon in the metropolis. Carbon stocks are low in the urban center and increase progressively towards the periphery of the city (Figure 4.5). In the peripheries, the high SOC stocks are confined to the east and west wings of the city. Carbon stocks in the north and south ends of the city are similar to that of the center. No correlation was found between aboveground vegetation carbon and soil organic carbon ($r = 0.10$, $p = 0.2982$).

Table 4.6 Summary of Kumasi's total carbon stocks: below- and above- ground in different green spaces. 1 Gg = 1,000 t.

	Belowground carbon (Gg C)		Aboveground (Gg C)		Total (Gg C)
UGS[1]	Soil	Root	Trees	Crops/Herb	
Plantation	95 (14.7)	26 (0.12)	307 (1.1)	0.0	428 (15.9)
Natural forest	27 (3.4)	43	365 (5.2)	0.0	435 (3.4)
Home garden	851 (96.3)	64 (1.3)	435 (10.5)	4.3 (7×10^{-4})	1,355 (108)
Institutional compound	272 (70.7)	90 (0.4)	667 (3.6)	0.0	1,028 (74.8)
Farmlands	105 (16.1)	9 (0.2)	68 (2.3)	0.8 (1.2×10^{-3})	182 (18.6)
Cemeteries	5 (1.1)	1 (0.03)	8 (0.22)	0.04 (5.9×10^{-4}	14 (1.4)
Public parks	14 (4.5)	6 (0.008)	68 (0.07)	0.0	88 (4.4)
Grassland	209 (39.0)	3 (0.13)	16 (0.8)	1.4x10-3 (2×10^{-7})	228 (39.9)
Total	1,577 (245.7)	242 (2.3)	1,934 (23.9)	5.1 (1.8×10^{-3})	3,758 (266.5)

[1]UGS = urban green space

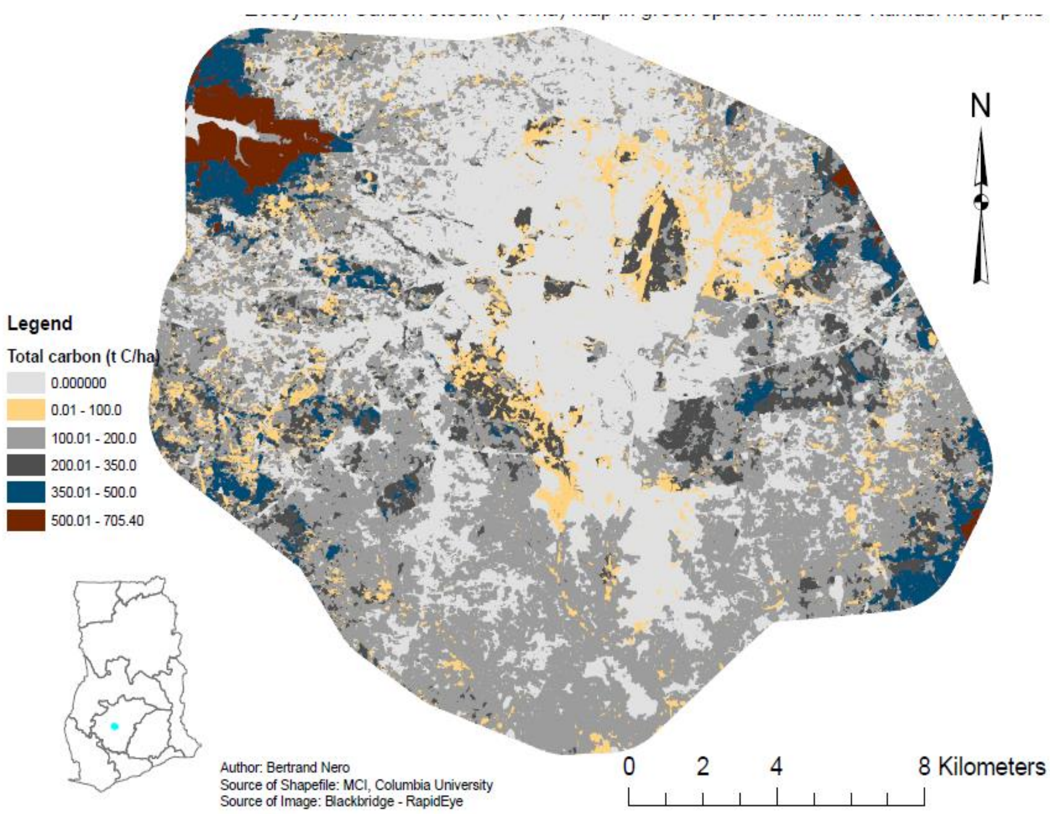


Figure 4.4 Map of UGS carbon storage (below + aboveground) in Kumasi metropolis.

4.4 Discussion

The quantification of organic carbon pools in the city of Kumasi provides valuable data for incorporation into the national carbon budget. As a signatory to the UN Framework Convention on Climate Change and the Kyoto protocol, Ghana, like many developing countries, has demonstrated its commitments to reduce emissions of GHGs and has put in place, among others, several policy frameworks geared at meeting the targets of these conventions. The Ghana government national climate change policy, although silent on the role of cities explicitly, inter alia committed to pursue low or neutral emission development through efficient sustainable energy and infrastructural development and expansion of carbon sinks via natural resources management including forest, agriculture and aquatic resources (MEST 2013). Similarly, the urban development policy of Ghana, aiming to improve environmental quality and adhere to climate change adaptation and mitigation stipulations, categorically advocates for the protection of green spaces from physical development and encroachment in cities (MLGRD 2012). This notwithstanding, the contributions of UGS to climate mitigation in Ghana have hardly been assessed, despite burgeoning global efforts to admit urban forest carbon credits to national and regional carbon markets (Poudyal et al., 2011).

The findings of this study suggest that the current national estimates of vegetation carbon do not adequately account for this ecosystem service within SSA cities (Henry et al., 2011). Kumasi's overall carbon pool is estimated at 3,758.1 Gg C which is roughly evenly partitioned in below- and aboveground components. Soils to 60 cm depth stored 42 % of the total ecosystem C pool (excluding buildings and furniture, landfill sites, people, etc) with roots and aboveground vegetation, respectively, holding 6 % and 52 %. Carbon storage is greater in the LDUZ (periurban) compared to HDUZ (core urban). Similar discrepancies have been shown in the UK and Germany where national carbon estimates undervalued carbon stocks of cities (Davies et al. 2011; Dorendorf et al. 2015). Comparison of Kumasi's carbon stocks to cities in the global north is necessitated by the paucity of similar data in tropical cities.

The total aboveground vegetation carbon in Ghana is estimated to be 1,158 Tg C (1Tg = 10^6 t, Henry et al. 2011), meaning Kumasi's vegetation C accounts for 0.2 % of Ghana's total aboveground C store, but represents only 0.1 % of its land area (Ghana's land area = 239,460 km^2). When soil C pool is included the proportion might be considerably higher.

The organic carbon storage in the city is unevenly distributed especially when built-up infrastructure are assumed to have no organic carbon. Urban green spaces such as public parks, institutional compounds and cemeteries have high carbon storage values in the core (HDUZ) areas. The outer fringes are, however, most relevant for carbon storage, mainly due to large forest patches or tree congregations and wetlands (Figures 4.2, 4.4, and 4.5). The importance of sparsely built-up areas in carbon storage is illustrated by comparing "core-urban" or HDUZ to "peri-urban" or LDUZ in the city. Assuming no carbon storage in buildings and compacted bare surfaces, the significant difference in carbon stocks between the two zones suggest that a definition of "urban" following political boundaries and not based on vegetation density could easily have resulted in misestimate of the total carbon storage of Kumasi.

The lopsided partitioning of organic C in favor of trees in Kumasi contradicts what is commonly observed in cities in the global north (Churkina et al. 2010; Edmondson et al. 2012;

Dorendorf et al. 2015) where about two-thirds of the urban ecosystem carbon pool is stored in the soil. Generally, trees in Kumasi were relatively larger (in both girth and height) than the average urban tree in these northern cities. However, larger differences in SOC can be attributed to the relatively higher temperature and moisture regimes in Kumasi which tend to accelerate decomposition, a characteristic of tropical environments. It is noteworthy that citywide vegetation and soil carbon in Kumasi are consistent with vegetation and soil carbon storage of 204 and 327 t C/ha, respectively, in the neighboring moist-deciduous forest (Adu-Bredu et al. 2011). In tropical forests of Africa, soils contribute about 40 % of ecosystem carbon storage (Henry et al. 2009; Henry et al. 2011), consistent with the findings of this study in Kumasi.

A hypothesis of this study asserted that carbon storage was similar regardless of UGS type for both vegetation and SOC. In contrast, carbon storage in UGS differed significantly. Natural forest had the highest vegetation carbon. However, the high standard errors in this green space type (Table 4.3) lead to uncertainties in carbon estimates, hence comparisons with other UGS types and neighboring land uses in the hinterlands may not be warranted. Nevertheless, it creates room for further investigations, as the small sample size and plot area for such large forest trees could have accounted for the incongruent error.

Public parks, cemeteries, institutional compounds in both the core (HDUZ) and peri-urban (LDUZ) areas store more carbon compared to the other UGS except in the natural forests. These high C storing green spaces were stocked with some of the largest and predominantly native tropical tree species in this region. The proportion of large trees and tree densities (Nowak 1993; Liu and Li 2012) and the species composition, diversity and land use (Jo 2002; Timilsina et al. 2014) are major drivers of carbon storage in plant ecosystems. Many native slow growing tree species tend to have high wood densities (specific gravity), a major parameter in C stock estimation apart from size. Though plantations have numerous trees per stand, the carbon they store is generally lower than that of the natural forest because of the small sizes of trees (except for the largest Kapok tree in this study found on a plantation which skewed the result) and because of simpler species composition (mostly pure stands of *Tectona grandis*, *Gmelina arborea* and *Senna siamea*). Farmlands, home gardens, and grasslands store the lowest carbon because of smaller sizes of trees in home gardens and fewer trees per area in farmlands and grasslands. A multiple of factors therefore account for the vegetation carbon storage differences among green spaces in the city. This is especially relevant for urban authorities when designing a city to meet ecological, economic and political interests.

Unlike tree carbon, soil organic carbon stocks closely corroborate the area coverage of the UGS type with home gardens, institutional compounds and grasslands in decreasing order having the highest soil carbon stocks to 60 cm depth (Table 4.5). Urban green space SOC stocks in decreasing order were farmlands, plantations, natural forest and public parks. These patterns are a reflection of differences in area coverage of each green space type and the SOC stored as UGS with largest area coverage (Table 4.3; Figure 3.6) tended to store the highest SOC (Table 4.4). Home gardens and institutional compounds are artifacts of human management and hence the findings here are consistent with the 65 % urban SOC stocks under residential green spaces in six cities in the United States of America strengthened primarily by area extent and high SOC storage (Pouyat et al. 2006). Although cemeteries contain relatively higher SOC, the total SOC stock was low because of the small area extent of this green space. Since cemeteries could not be completely mapped because of lack of resources to traverse all communities within the city to track locations of cemeteries, the precise quantification of their total carbon stocks was obscured.

The relatively higher SOC in home gardens, plantations and institutional compound over soils of other UGS types were not particularly surprising. Indeed, home gardens in Kumasi benefit from waste water irrigation and organic waste including animal dung amendments whiles trees on institutional compounds if on lawns occasionally receive extra water amendments. Plantations are particularly heavily littered with human excreta and/or household waste which are a major source of nutrients (carbon and nitrogen). This perhaps explains the significantly higher SOC in the top 0 -15 cm for plantations compared to other UGS types (Table 3). In spite of geographic, climatic and soil differences, the SOC storage (46 – 111 t C/ha) to 60 cm depth of green spaces in Kumasi were comparable to SOC in green spaces in cities in Europe (Dorendorf et al., 2015; Edmondson et al., 2014, 2012) and in North America (Pouyat et al. 2006; Yesilonis and Pouyat 2012; Campbell et al. 2014). In general, higher organic carbon in soils under residential vegetation in these cities in the Global North are a reflection of intensive management and inputs in home lawns and domestic gardens (Pouyat et al. 2006; Edmondson et al. 2012; Edmondson et al. 2014) and to some extent climatic differences.

Low pH owed to less human disturbance and limited inputs from external sources (Bationo et al. 2006) and addition of organic acids, including increased uptake of base cations by trees (Berthrong et al. 2009), may have caused the significantly low SOC concentrations of the preserved natural forest (Owabi catchment) and the KNUST botanic garden in Kumasi. The high productivity of the natural forests reflect high nutrient uptake rates, consequently freeing cation exchange sites for attachment of H^+ ions. Whereas the link between low pH and SOC depletion is still nebulous, acidification of soils modifies organic matter quality (Kanianska et al. 2014).

Excluding wet forest SOC in Kumasi metropolis, wetlands hold 114 t C/ha in soils to 60 cm depth being only marginally greater than SOC in cemeteries and home gardens. Periodic or permanent inundation, which is a characteristic of wetlands, alters pH and suppresses oxidation and aerobic microbial activity resulting in accumulation of carbon (Schoenholtz 1994; Londo 2000). From organic matter concentrations determined for wetlands in Kumasi (Campion and Owusu-Boateng 2013), the mean SOC was estimated to be about 176 t C/ha to 23 cm depth which is similar to the estimates in this study. Higher wetland SOC may also be attributed to human activities (i.e. waste disposal, mechanical shops, wood works, etc) on the immediate banks of these wetlands (Campion and Odametey 2012). Furthermore, a citywide study of soil carbon in Hamburg, Germany, revealed wetlands, including wet forest soils, hold the highest SOC of 144 t C/ha among other land uses (Dorendorf et al. 2015), further underlining the importance of conserving urban wetlands in cities.

By virtue of the high concentrations in the upper most soil depth, this layer is very important to climate change mitigation not only because it is the recipient of most organic debris but also because it is most vulnerable to disturbances and is the main source and shield against upward losses of carbon and other GHGs from the subsoil. In the soils in Kumasi, 30 % of the SOC to 60 cm depth was held in the top 15 cm depth, 27 % in 15–30 cm layer and 43 % in the 30 – 60 cm layer (Table 4.5). This is comparable to the 42 % C in the top 20 cm of Leicester city soils measured to 1m depth (Edmondson et al. 2012) and more so to the 52 % SOC in the top 30 cm layer of soils in Africa (Henry et al. 2009) . Disturbances, conversion to grey (built-up areas) spaces, and poor management of these soils can cause massive losses of carbon and other GHGs especially from the A-horizon (surface soil layers).

Aside the unusually high vegetation and low soil C stocks in remnant natural forest in the city, C stocks for the other UGS types were fairly comparable to C stocks in land uses in the neighboring hinterlands. Vegetation carbon storage in plantations in this study were similar to carbon stocks in regular tree and fruit tree plantations within the forest belt of Ghana (Adu-Bredu et al., 2008; Kongsager et al., 2013). Aboveground C stocks of public parks, institutional compounds and cemeteries were within the range often reported for forest tree carbon stocks in the region (Adu-Bredu et al., 2011; Lewis et al., 2009). Soil organic carbon under plantations were similar to those of plantations in rural dry forest but less than SOC under plantations in the moist forest zone with 48.8 and 38.3 t C/ha C in 0-20 and 20-40 cm depths, respectively (Adu-Bredu et al. 2011). Similarly, SOC in urban farmlands were less than those of cultivated fields in the moist forest region but greater than SOC in cultivated fields in the dry forest region of Ghana (Adu-Bredu et al. 2011) and in cocoa farmlands (Asase et al. 2011). Nutrient enrichments from organic waste and human excreta plus other urban environmental inducements (N deposition, CO_2 enrichment, light, high temperatures), can provoke higher urban vegetation productivity than natural forests in the hinterlands (Gregg et al. 2003; Hutyra et al. 2011; Searle et al. 2012; Davis et al. 2015). Thus, the findings here partially corroborate previous findings that SOC in soils under urban crops and trees were higher than neighboring rural farm and forest lands (Pouyat et al. 2006; Yesilonis and Pouyat 2012; Raciti et al. 2012; Edmondson et al. 2012; Edmondson et al. 2014). Estimation of national carbon stocks ought to consider incorporating urban carbon stocks into the national and regional carbon budget.

4.5 Conclusion

This chapter examined the potential of cities in developing countries to partially mitigate some of the GHGs they emit into the atmosphere using in-city ecological networks. It is evident that cities in Africa have significant carbon stocks in their green spaces, similar to or even more than cities in the developed north. The large carbon stocks in Kumasi clearly makes a case for the inclusion of cities in the national and regional carbon assessments in Africa. Below- and aboveground carbon storage combined account for 45 % of citywide annual emissions in Kumasi. Hence, integrating ample quantities of vegetation into cities in Africa will be essential in boosting urban sustainability and mitigating local GHG emissions and climate change.

Green space type has a strong influence on the allocation of carbon to the topsoil and ecosystem carbon. Tree dominated green spaces (public parks and natural forests with limited inputs and human interference) sequester more carbon in aboveground vegetation while green spaces closely associated with built-up areas and rampant human activity (home gardens, plantations and institutional compounds) store more carbon in soils. Soil C is the most relevant C pool in grass and farmlands. Therefore, to enhance carbon sequestration and other climate change benefits of ecological systems in cities, conservation and management of tree dominated green spaces are key. In addition, greening bare areas with grass and trees and planting streets with trees on the side could greatly boost the carbon stocks of the city. Since the outer regions (LDUZ) have more carbon than the core (HDUZ) of the city, greening the HDUZ without compromising the stocks in outer edges should be a priority of the city authorities.

This is one of few if any studies to discuss carbon storage at a citywide scale in sub-Saharan Africa and the findings could be an important addition to the already expanding global database on urban carbon storage and contribute positively to policy discourse on urbanization and global climate change. They are particularly timely and relevant to both national and local governments, as many African nations garner efforts to realign national and urban climate change policies geared at minimizing emissions and creating a conducive carbon neutral society. The findings are by no means exhaustive and both within and inter-city investigations will be essential to strengthen the interlinkages between urban green spaces, carbon sequestration and other ecosystems services derived from cities.

The current study quantified and mapped carbon stocks in green spaces of Kumasi but not the carbon stocks for the anthropogenic pool (i.e. SOC under impervious surfaces, C stocks in buildings and people, and C stocks in landfill sites). Estimating carbon storage and emissions from the urban anthropogenic pool will advance our understanding of the contribution of cities in the Global South to the global carbon budget and climate change mitigation.

5 TREE AND TRAIT DIVERSITY, COEXISTENCE AND DIVERSITY-FUNCTIONAL RELATIONS OF GREEN SPACES IN KUMASI, GHANA

5.1 Introduction

Change in biodiversity is a global change with important and sometimes irreversible ecological and social impacts (Chapin et al. 2000). Furthermore, a challenge confronting contemporary ecology is the paucity of knowledge about biological diversity on earth (including cities) (Mora et al. 2011). This is even murkier in cities in developing countries in that urban biodiversity concerns are not merely subsidiary to more pressing issues such as unemployment, poverty alleviation (Anderson et al. 2013), national biodiversity strategies and most assessments neglect urban biodiversity outright (MES 2002; Hackman 2014). Consequently, empirical and conceptual understanding of the biological diversity and the fundamental principles behind plant community assembly and function in cities remain elusive.

Historically, ecological studies in cities treated urban areas as single habitats (Burton et al. 2005; Pauchard et al. 2006; McKinney 2008) or were conducted at broad spatial scales that blurred the distinctions in microhabitat effects in cities (Ellis and Ramankutty 2008). However, urban landscapes consists of severely fragmented and heterogeneous habitats (green spaces) which may prescribe varied savage consequences on patterns of species diversity, abundance and distribution (Savard et al. 2000; Pauleit et al. 2005; Angold et al. 2006; Savage et al. 2015). Such fine-scale heterogeneity in habitats are important forces structuring animal species assemblages within cities (Savage et al. 2015). For plants, which are sessile and restricted in distribution by ecological and social filters, analysis of the array of heterogeneous fine-scale green space (microhabitat) types in cities may reveal new patterns underpinning urban communities and important for global biodiversity conservation.

Urbanization also causes shifts in plant species traits with many urban plant species being wind-pollinated, scleromophic or animal dispersed (zoochory) (Knapp et al. 2008) and mostly pioneers (Glaeser 2006; Huang et al. 2013). Such changes in urban species and trait compositions can have important consequences on ecosystem productivity and hence the amount and variety of ecosystem services they deliver. In natural habitats, high productivity or ecosystem function is associated with high species diversity or richness (Naeem et al. 1994; Reich et al. 2001; Bezemer and Van Der Putten 2007) or to trait and functional group diversity and richness (Hooper and Vitousek 1997; Hector 1999; Roscher et al. 2012). Although most urban areas are uniquely heterogeneous in terms of green spaces (patches) and species, plant species traits or functional groups can be uniquely similar (McKinney 2006; Knapp et al. 2008a) due to environmental selection pressure favoring only closely related species (Williams et al. 2008). Such species and/or trait plasticity in cities results in plants with high affinity for nutrient-rich warm habitats, high irradiance, and recurrent disturbance (Burton et al. 2005; Knapp et al. 2008b; Lososova et al. 2008; Albrecht and Haider 2013). Hence, maintaining a variety of green spaces in urban landscapes are encouraged to enhance species and functional group diversities which intend accelerate ecosystem function and diversify the range of ecosystem services they provide.

While, urban floral diversity is critical to providing ecosystem services and improving human wellbeing, preserving local diversity, averting environmental change, promoting environmental education, and providing contact with nature (Dearborn and Kark 2010), it remains threatened by both anthropogenic and environmental consequences due to the process of urbanization (Seto et al. 2012; Mcdonald et al. 2013) and research linking floral species and functional groups (functional types or life history traits) to ecosystem processes/functions such as carbon sequestration and storage in tropical cities is lacking (Wright et al. 2006). Furthermore, a unifying theory to explain species distribution and coexistence (Griffin and Silliman 2012) is an unknown subject in urban plant diversity studies. Aronson et al. (2014) underscored the dearth of urban biodiversity data from tropical cities and the immediate need for research in the current frontiers of urban ecology. Hence, this chapter seeks to fill these knowledge voids using a case study in Kumasi, Ghana. Knowledge of species co-existence in any ecosystem is relevant to the restoration, conservation, and management of such ecosystems as well as enhancement of their functions.

The goal of this chapter is to examine tree diversity patterns of UGS and the linkages between ecosystem diversity and function. It is hypothesized that the niche space limits tree species abundance distribution in cities and that green spaces which are more species rich are more productive. It is also hypothesized that species life history traits are essential determinants of species productivity at the tree level. These objectives were pursued using inventory and survey techniques and were combined with species abundance modeling.

5.2 Methodology

5.2.1 Study area

Refer to chapters 3 and 4.

5.2.2 Sampling procedure

Refer to chapter 4 - Trees in each sample plot were identified to the species level and number of each species present counted and recorded. Understory vegetation rarely exist in these green spaces, and hence were not sampled. Tree identification was carried out with the aid of tree experts and published tree identification guides such as those by Hawthorne and Gyakari (2006) and Oteng-Amoako (2002).

5.2.3 Species richness and diversity estimation

Species richness for each green space type, urban zone and for the entire city were calculated. In addition, expected species richness for UGS type and urban zone was computed using Chao1. *Chao1*, the simplest nonparametric estimator estimates total number of species (Sest) by adding a term that depends only on the observed number of singletons (a, species each represented by a single individual) and doubletons (b, species each represented by exactly two individuals) to the number of species observed (Sobs) (equation 5.1, Chao et al. 2006);

$$Sest = Sobs + \frac{a^2}{2b} \qquad (5.1)$$

Shannon (H) and Simpson (D) indices which combine richness and evenness parameters and Pielou (J), a measure of evenness, were also estimated. Both Shannon and Simpson diversities increase as richness increases for a given pattern of evenness and the vice versa. Differences in species richness among UGS were established using Chi-square test.

To determine species similarities/dissimilarities among UGS types and urban zones, beta diversity between UGS and among urban zones were estimated. Beta diversity is the difference in alpha diversity (habitat species richness) between two areas/sites or spatial variation in species composition (Wilson and Shmida 1984). Beta diversity was estimated with the reformulated Sørenson and Jaccard indices proposed by Chao et al. (2005) instead of the binary techniques previously employed. Binary techniques often fail to account for missing or unidentified species and assume both rare and common species have equal weighting (Krebs 2014). To circumvent this short-coming, a probabilistic approach which combines the incidence-based indices with relative abundance data to compute these adjusted indices was used, thus minimizing bias and placing unequal weightings on rare and common species (Chao et al. 2005). The adjusted Sørenson's and Jaccard's indices are given in equations 5.2 and 5.3 respectively.

$$\text{Sørenson's Adjusted Index} = \frac{2UV}{U+V} \tag{5.2}$$

$$\text{Jaccard's Adjusted Index} = \frac{UV}{U+V-UV} \tag{5.3}$$

Where

$$U = \sum_{i=1}^{D12} \frac{Xi}{n} + \frac{(m-1)}{m}\left(\frac{f+1}{2f+2}\right) \sum_{i=1}^{D12} \frac{Xi}{n} /(Yi = 1) \tag{5.4}$$

$$V = \sum_{i=1}^{D12} \frac{Yi}{m} + \frac{(n-1)}{n}\left(\frac{f1+}{2f2+}\right) \sum_{i=1}^{D12} \frac{Yi}{m} /(Xi = 1) \tag{5.5}$$

Where

/(expression) = indicator function (/=1 if expression is true, /=0 if false)

Xi = number of individuals of species i in sample 1

D12 = number of shared species between samples 1 and 2.

n = total number of individuals in sample 1

m = total number of individuals in sample 2

f_{+1} = observed number of singletons (species with exactly 1 individual) in sample 1

f_{+2} = observed number of doubletons (species with exactly 2 individuals) in sample 1

Yi = number of individuals of species i in sample 2

f_{1+} = observed number of singletons in sample 2

f_{2+} = observed number of doubletons in sample 2.

When f_{+2} = 0 or f_{2+} = 0, replace that particular denominator by +1. If the value of U or V is greater than 1, then it is replaced with the value of 1.

The assumption of unity where observed doubletons is equal to zero is one of the caveats of this approach. Another caveat is that it does not address incidences where no similar singletons exist in a pair of samples. The values of both adjusted Jaccard's and Sørenson's coefficients range between 0 and 1: with a value of 0 implying absolute dissimilarity and a value of 1 implying absolute similarity (Koleff et al. 2003; Chao et al. 2006). Thus, high values reflect low Beta diversity (high similarity) and low values reflect high beta diversity (high dissimilarity). Undesirable biases may result from inequality in sampling efforts or variation in spatial scale of sample habitats (Koleff et al. 2003).

5.2.4 Correspondence analysis

Correspondence analysis (CA) was performed to show the association between tree species, UGS type and urban zone or stratum (HDUZ, LDUZ). Correspondence analysis locates species simply by the average position of the samples in which they occur and locates samples by the mean position of the species included. Species abundance data were used to generate axis scores. Detailed application of CA in tropical tree diversity studies are reported by Anglaaere et al. (2011) and Fayolle et al. (2014).

Correspondence analysis accommodates all types of categorical variables whether binary, nominal, or ordinal and does not require the underlying fulfillment of any distributional assumptions (Sourial et al. 2010). It graphically displays the relationship between variables which otherwise would not be detected using pairwise test of associations. The graphs represent relative frequencies based on the distance between row (green space or urban zone or stratum) and column (species) profiles and the distances to the average row and column profiles in a low dimensional space. The distance is measured as a chi-square metric. A map of the first and second dimensions of the CA was generated.

5.2.5 Model fitting

To find a theoretical explanation to the basis of tree species co-existence in urban areas, the species abundance distributions (SAD) obtained from this study were fitted to three community ecological models: geometric series (GS) and Broken-Stick (BS) models with the primary focus on niche apportionment (Tokeshi 1990) and the lognormal (LN) model, which reflects unperturbed communities under the influence of multiple environmental factors.

The niche apportionment models are most applicable in cases where a few factors (e.g. light) dominate the ecology of the assemblage. Both GS and BS models assume that the fraction of niche space occupied by each species is proportional to its relative abundance and that the relative proportions of the species are in equilibrium. However, the models differ in how the niche space is sub-partitioned, resulting in differences in evenness.

The BS model depicts a simultaneous random division of a resource space into species' niches (i.e. species share a specific resource or factor evenly) (Wilson et al. 1996). This results in a curve with few abundant species, several species with intermediate abundance and a tail with rare species.

Similarly, the GS model, often referred to as the niche pre-emption model, assumes that the abundance of a species is directly proportional to the amount of resources it utilizes such that the most abundant species consumes k amount of resources (Magurran 2004; Fattorini 2005). The next most abundant species consumes k amount of resources from the left over and the trend continues until the entire space is occupied (resources are exhausted). This results in a geometrically decreasing sequence of species abundance. Communities in early stages of succession as well as disturbed communities usually fit the geometric model (Magurran 2004; Caruso and Migliorini 2006).

The lognormal distribution assumes that there are few species with high and low species abundances and several species with intermediate abundances. It is modeled based on Sugihara (1980) model in which a given resources space is sequentially divided into niches, thus, resulting in a curve slightly similar to that of the Broken-stick model but is more highly parameterized and more flexible in shape.

Both GS and BS models were fitted using regression techniques involving species abundance and the rank in abundance of the species (Fattorini 2005). In the GS model, species abundance is log transformed (eq. 5.6) whereas in the BS model, the rank in abundance is log transformed (eq. 5.7). Hence, the following models were depicted:

$$\log A = b_0 + b_1 R \quad (5.6)$$

$$\log R = b_0 + b_1 A \quad (5.7)$$

Where A = abundance of species, b_0 and b_1 represent regression coefficients and R = rank in abundance.

The regression approach is more robust in selecting the best fit model from among competing models, precludes the need to adhere to the assumptions of chi-square test and estimates expected frequencies (Fattorini 2005).

The lognormal distribution is a plot of the number of species as the ordinate and the logarithm of the abundance as the abscissa. A bell-shaped curve reveals a normal distribution in the data. This approach was cross-checked by plotting cumulative species richness on the probit scale against logarithm of species abundance. A diagonal straight line of the plot indicates that the data is normally distributed.

However, several caveats underlie the use of biological or statistical models as basis to provide explanations to community assemblages: 1) a natural community conforming to a specific SAD model does not in itself justify the assumptions of the model, hence inferences about the community should be made with caution, and 2) an assemblage may assume the assumptions of more than one of these models (Magurran 2004).

Using life history traits of the plant species as proxies for the environmental factors regulating the urban tree assemblage, the possible environmental filters underpinning species coexistence (fitted model) are discussed. The environmental filter (abiotic) such as light using guild type as surrogate and biotic filters, using dispersal mechanism as proxy were examined.

5.2.6 Life history traits

From literature, plant species were classified into several guild types or life history traits. The main dispersal mechanisms of trees were zoochory (animal), anemochory (wind), anthropochory (humans), hydrochory (water), barochory/autochory (gravity/natural fall). Species were also classified into guild types: pioneers (heavy light demanders which grow in gaps), non-pioneer light demanders (intermediate light demanders of which seedlings occur in shade and the adults in full light), and shade-tolerant species (both young and adults tend to be abundant in the forest understory). Species were further grouped according to leaf longevity (deciduous and evergreen), main reproductive mechanism (seed, vegetative or both), and origin (native or exotic). Functional traits (i.e. leaf area) and common uses of each species found in the literature were extracted. Plant traits were obtained from the Agroforestry database 4.0 (Orwa et al. 2009) and the TRY global database of plant traits (Kattge et al. 2011). Life history traits among plants in the HDUZ (core urban), LDUZ (peri-urban) and natural forest (Owabi sanctuary) were analyzed using chi-square test and principal component analysis (PCA). Twelve life history traits of tree species in conjunction with species abundance data were analyzed with PCA, using ones as prior communality estimates. Components were extracted using the principal axis technique followed by a varimax (orthogonal) rotation. Factor scores generated from the PCA were used in a multiple regression against mean tree species carbon storage, and species abundance in the area. Mean carbon densities for each green space type were correlated with UGS total species richness. Life history traits of the plant species were used as proxies for the environmental factors as well as social and biotic factors regulating the urban tree assemblage to analyze and extract possible factors shaping the plant community. All statistical analyses were performed using SAS and Stata.

5.3 Results

5.3.1 Species richness

Overall 3,757 individual trees and shrubs made of 176 species and 42 families were sampled across the different UGS types in Kumasi, excluding the neighboring

Owabi wildlife sanctuary (Appendix 1). Using Chao1 richness estimator, a possible total woody species richness of 222 was estimated. When the species richness data of a natural forest within the Owabi wildlife sanctuary in the peri-urban zone of Kumasi is added, the actual species richness of Kumasi metropolitan area rises to 224. Owabi sanctuary has tree and shrub species richness of 96 (FC 2014).

In contrast to the null hypothesis of even species richness among green spaces, a chi-square test revealed otherwise ($p<0.0001$, $n = 8$, $X^2 = 139.4$). The most species rich UGS are home gardens, institutional compounds and public parks with species richness of at least 75 (Table 5.1). Grasslands and farmlands have the least species richness of 6 and 23, respectively. Rare species, were quite prevalent, with public parks having the highest number of rare species (singletons = 37, doubletons = 13). The natural forest included the species from the Owabi sanctuary.

Table 5.1 Tree species abundance, richness, and diversity indices in different green space types within Kumasi. Chi-square analysis of richness indicates significant differences ($p<0.0001$, $n = 8$, $X^2 = 139.4$).

Greenspace Type	# of Individuals	Observed Species Richness, S	Estimated Chao1 Sest	Shannon H	Simpson λ	Pielou J (Evenness)
Plantation	630	48	73.6	2.561	0.146	0.66
Natural forest	980	96	105	3.84	0.031	0.84
Home garden	1,095	80	98.6	3.158	0.081	0.72
Institutional Compound	715	79	101.3	3.502	0.049	0.80
Farm	100	23	47.0	2.269	0.179	0.72
Cemetery	266	51	81.3	3.242	0.065	0.82
Streets	565	37	57.2	2.809	0.097	0.78
Public park	334	75	127.7	3.521	0.048	0.82
Grassland	39	6	8.3	0.749	0.672	0.42
Total	3,757	176	222.4	3.716	0.044	0.72

Shannon's and Simpson's diversity indices indicate a high diversity ($H>3.0$ and $\lambda <0.08$) in home gardens, institutional compounds, cemeteries, and public parks. This implies that these green spaces have an equivalent diversity (exponent of Shannon H) with at least 20 equally common species. The grassland had the least diverse tree species ($H = 0.75$, $\lambda = 0.67$). These diversity and evenness indices describe the community structure, reflect the effective number of species with equivalent diversity and indicate ecosystem function (Heip et al. 1998). Pielou's evenness for tree species in Kumasi ranged between 0.42 in grasslands (less even) and 0.84 in the natural forest (more even).

Species richness in the HDUZ (core urban) and LDUZ (peri-urban) areas of Kumasi were, respectively, 108 and 142. Chi-square goodness of fit test on species richness revealed a strong association between green spaces and zone of urbanization: HDUZ (core) and LDUZ (peri-urban) ($p<0.0001$, $n = 1$, $X^2 = 15.70$).

Figure 5.1A shows rank-abundance curves for tree species in different green space types within Kumasi. Green spaces are dominated by a few abundant species and several rare species and display similarities in evenness. The difference in evenness is depicted in the steepness of the rank-abundance curve of the green spaces. Generally, the steeper the curve, the more uneven the distribution of individual species within the UGS type (Figure 5.1A). In this light, grasslands and farmlands contain the least number of tree species and are the most uneven. All other green spaces have a few very abundant and several rare tree species.

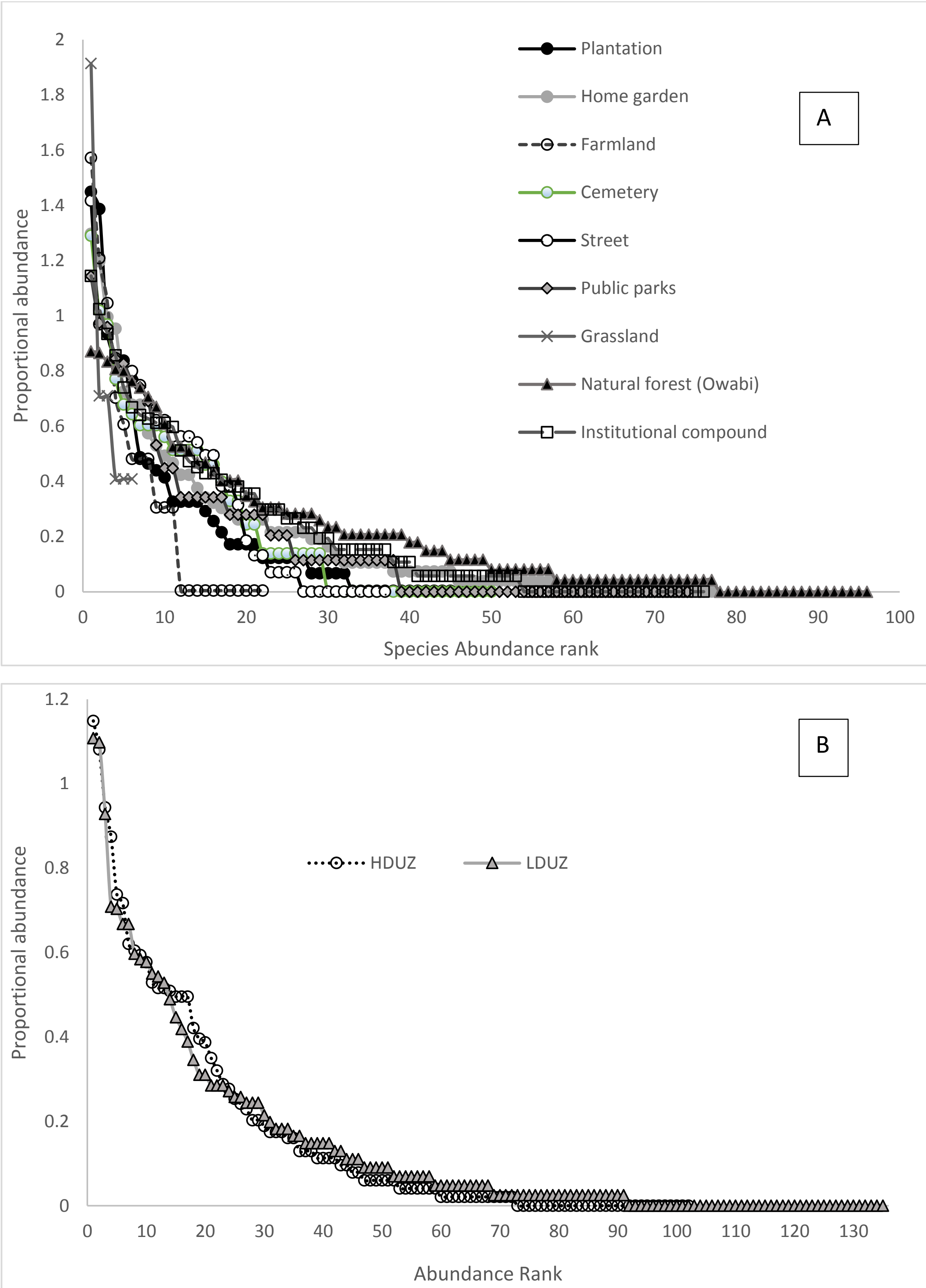


Figure 5.1 Tree species rank-abundance curves for different green space types (A) and different urban zones (B) in and around Kumasi metropolis. HDUZ; - High density urban zone (core urban); LDUZ - low density urban zone (peri-urban).

Table 5.2 displays tree species richness and diversity indices in two urban zones and a neighboring natural forest within the KMA area. A chi-square goodness of fit test showed significant differences in species richness between the urban zones (core urban (HDUZ), peri-urban (LDUZ) and natural forest, $p = 0.0096$, $\chi^2 = 9.3$). The city's (core+peri-urban) richness of 176 (in a green area = 1,230 ha) is greater than that of the neighboring natural forest in the Owabi sanctuary (96 species, area = 860 ha). The HDUZ (S = 109, green area = 430 ha) and the LDUZ zone (S = 142, green area = 800 ha) also have more species than the forest in neighboring Owabi sanctuary. The pattern of species distribution in the urban (HDUZ), peri-urban (LDUZ), and natural forest were similar (Figure 5.1B). The pattern of species abundance distribution was similar for these zones were a few very abundant species, a couple of intermediary abundant species and several rare species. Species evenness of the natural forest (Owabi sanctuary) was slightly higher than the evenness in both HDUZ and LDUZ areas. A strong association was found in the species richness between UGS type and urban zone ($p = 0.001$, $n = 8$, $\chi^2 = 36$).

Table 5.2 Tree species richness, estimated species richness (Chao1), species diversity in urban, peri-urban and natural forest in the Kumasi metropolis ($p = 0.0096$, $\chi^2 = 9.3$, $n = 2$).

Urban Gradient	Total abundance	Species Richness S	Chao1 Sest	Shannon H	Simpson λ	Pielou J (Evenness)
Urban (HDUZ[1])	2025	109	152.2	3.5	0.05	0.74
Peri-urban (LDUZ[1])	1738	141	179.9	3.7	0.05	0.75
Urban_Total	3763	176	234.0	3.6	0.04	0.69
Forest (Owabi Sanctuary)	980	96	105.0	3.8	0.03	0.84

[1]HDUZ - High density urban zone; LDUZ - low density urban zone

5.3.2 Comparison of UGS species composition (Beta diversity)

High similarity in species diversity was set at ≥0.7 for the Jaccard and ≥0.8 for the Sørenson indices (Chao et al. 2006; Krebs 2014). Based on the Jaccard's index, species diversity in public parks was highly similar to those of plantations, home gardens, and streets (Table 5.3). Streets and cemeteries were also highly similar in species composition. Based on Sørenson's index, there was high similarity among the following: institutional compounds (IC) and plantations, IC and home garden, IC and public parks, cemeteries and farmlands in addition to the pairs listed under the Jaccard similarity index. Most green spaces were dissimilar in species composition while few were moderately (0.4 – 0.6) similar. Differences in species diversity among these UGS types possibly reflect the degree of human influence/management and environmental conditions selecting and determining the abundance of the species in each UGS type or urban zone.

The HDUZ (core), LDUZ (peri- urban) and natural forest (Owabi sanctuary) differ speciescomposition. The Jaccard and Sørenson indices for the HDUZ and LDUZ were 0.89 and 0.95, for HDUZ and the natural forest (Owabi) were 0.31 and 0.48, and for LDUZ and the natural forest (Owabi sanctuary) were 0.52 and 0.68, respectively. The number of shared species between HDUZ and LDUZ: core urban and natural forest (Owabi) were, respectively, 74 and 27 whereas 45 species were shared between LDUZ and natural forest. The order of exotic (non-natives of the afro-tropics) species richness and abundance in the three zones was HDUZ > LDUZ > natural forest (Figure 5.2). Native species constitute 90 % of the species pool in natural forest, 60 % in the LDUZ, and 45 % in the HDUZ.

Table 5.3 Similarity (Jaccard index, upper half of the matrix and Sørenson index lower half of the matrix) in species composition in green spaces within Kumasi. Values close to 1 indicate high similarity and close to 0 indicate high dissimilarity. Values in bold show strong similarity (≥0.7 for Jaccard and ≥0.8 for Sorenson).

	Plantation	Natural forest	Home garden	Institutional compound	Farmland	Cemetery	Street	Public Park	Grassland
Plantation		0.0478	0.626094	0.687981	0.312827	0.464112	0.479306	**0.803139**	0.337455
Natural forest	0.091203		0.05235	0.35583	0.042153	0.386403	0.122011	0.278104	0.089649
Home garden	0.77006	0.0995		0.68049	0.582489	0.600331	0.348514	**0.785932**	0.110204
Institutional compound	**0.81515**	0.5249	**0.80987**		0.36407	0.462401	0.629068	0.684673	0.246804
Farmland	0.47657	0.0809	0.736168	0.533803		0.679796	0.341412	0.308066	0.03925
Cemetery	0.633984	0.5574	0.750258	0.632386	**0.809379**		**0.757193**	0.590428	0.112862
Streets	0.648015	0.2175	0.516886	0.772304	0.509034	**0.861821**		**0.71221**	0.098618
Public Park	**0.890823**	0.4352	**0.880137**	**0.812826**	0.471025	0.742477	**0.831919**		0.127521
Grassland	0.504623	0.1646	0.19853	0.395899	0.075536	0.202831	0.179531	0.226198	

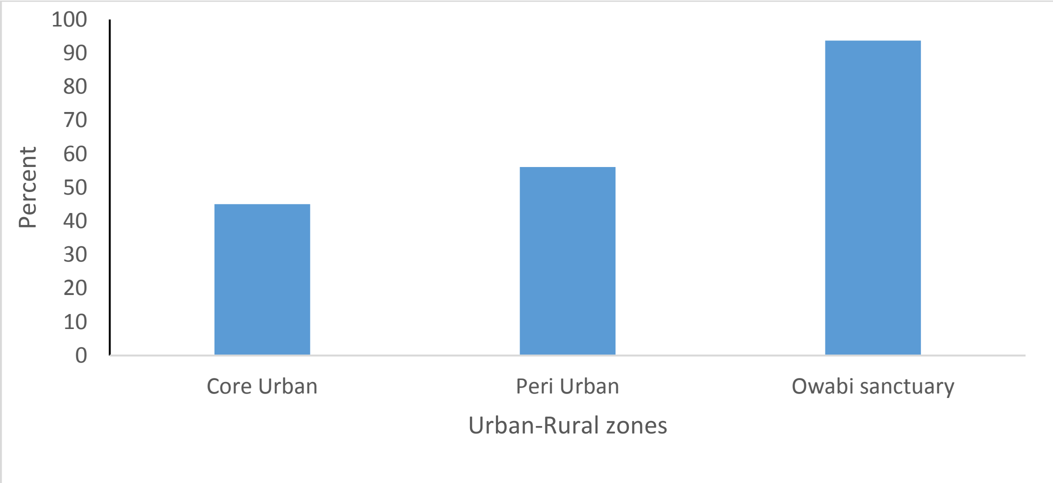


Figure 5.2 The proportion of native species in the tree species composition of the rural-urban zones in Kumasi metropolis: Core (HDUZ), peri-urban (LDUZ) and natural forest (Owabi sanctuary). [1]HDUZ - High density urban zone; LDUZ - low density urban zone

Correspondence analysis further reinforced similarity (proximity implies similarity) in species among green space types and urban zones. About 51 % of the association was represented well in two dimensions. Dimension 1 (x-axis) representing green space types, explained 28.5 % of the total variation. Striking similarities are found among plantations and grasslands; public parks, streets, and institutional compounds (IC); home gardens (HG) and farmlands; cemeteries and natural forest. Dimension 2 (y-axis), representing species, accounted for 22.1 % of the total variation. The most important deviation is the cluster around HG (negative dim2, negative dim1) and comprises mostly edible trees such as *Moringa oleifera*, *Psidium guajava*, *Citrus sinensis*, *Persea americana*, *Annona squamosa*, *Mangifera indica* etc. The 2nd most important deviation consists of species associated with the plantation-grassland cluster (positive dim2, negative dim1) and comprises: *Tectona grandis*, *Bambusa* vulgaris, *Hevea brasiliensis*, *Entadrophragma utile*, *Eucalyptus* spp., and a host of others (Figure 5.3). A 3rd prominent deviation is the cluster containing species in the natural forest (Owabi sanctuary) and cemeteries. It consists of native species such as *Antiaris toxicaria*, *Triplochiton scleroxylem*, *Piptadeniastrum africanum*, *Cola gigantea*, *Terminalia superba*, *Sterculia* spp., *Amphimas pterocarpoides*, *Cedrela odorata*, *Morus mesozygia*. Rule of thumb for the interpretation of the biplot: species near each other are most similar, UGS near each other are also most similar, species near a UGS mostly occur in that UGS.

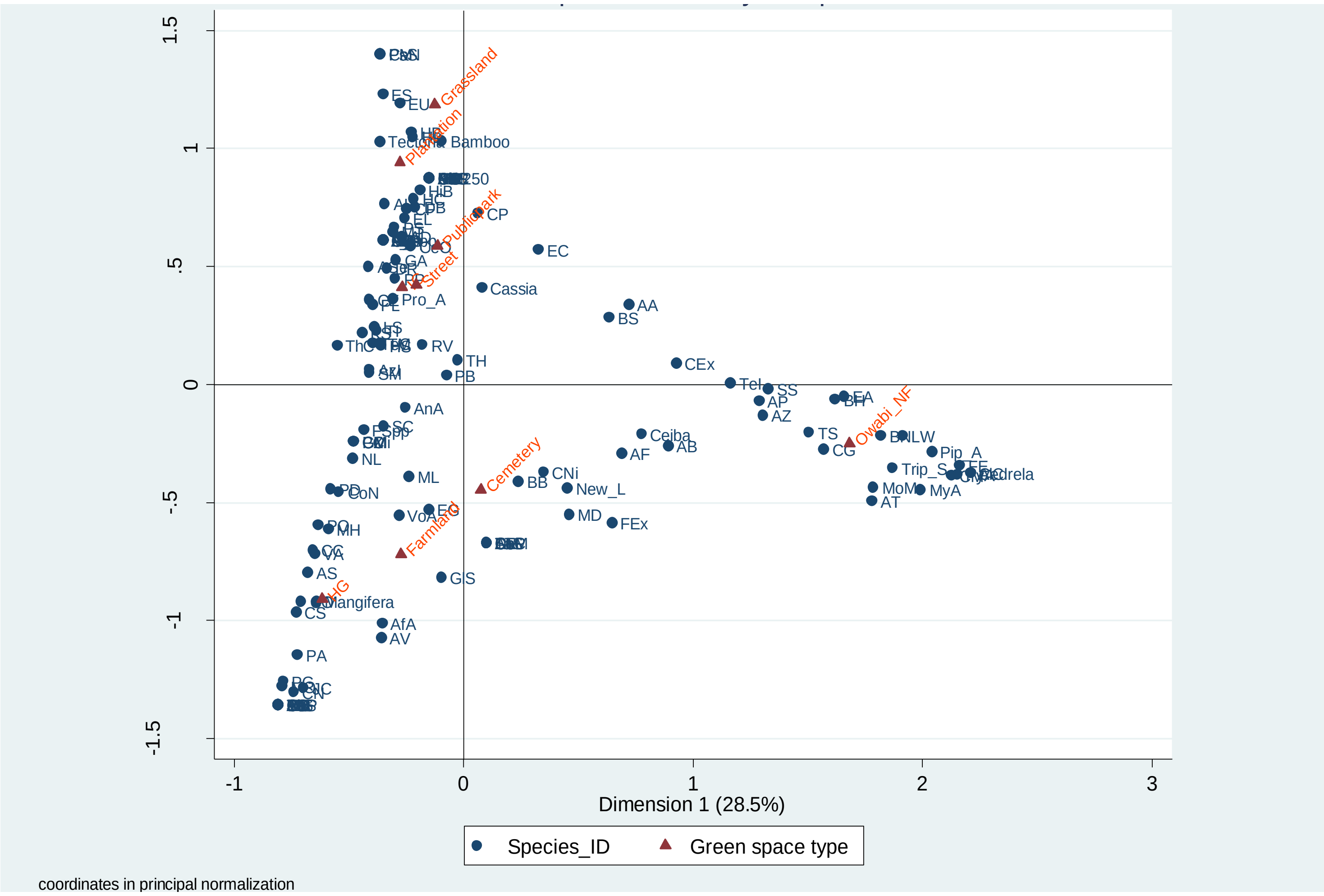


Figure 5.3 Output of correspondence analysis for the tree species in different (A) green spaces-urban zones interactions and (B) only green spaces in Kumasi metropolis. In B; Dimension 1 represent green spaces while dimension 2 represents plant species. Chi-square = 11169.8, Degrees of freedom = 2624. **Species names include**: AL, *Albizia lebbeck*; ASe, *Acasia senegale*; ASo, *Acalypha sonderina*; AD, *Adansonia digita*; AdP, *Adenanthera pavonina*; AfA, *Afzelia africana*; AF, *Albizia ferruginea*; AA, *A. adianthifolia*; AZ, *A. zygia*; AiC, *Alchornea cordifolia*; AlP, *Allanblackia parviflora*; AB, *Alstonia boonei*; AP, *Amphimas pterocarpoides*; AO, *Anacardium occidentale*; AM, *Annona muricata*; AS, *A. squamosal*; AnA, *Antiaris africana*; AT, *A. toxicaria*; AC, *Araucaria columnaris*; AI, *Artocarpus incisis*; AzI *Azadirachta indica*; AN, *Anthocleista vogelii*; AV, *A. nobilis*; Bamboo, *Bambusa vulgaris*; BN, *Baphia nitida*; BaS, *Baphia* spp.; BT, *Bauhinia tomentosa*; BS, *Blighia sapida*; BB, *Bombax buonopozense*; CaC, *Callitris cupressiformis*; CaP, *Calotropis procera*; CO, *Cananga odorata*; CP, *Carapa procera*; CaN, *Cassia nodiflora*; Cassia, *C. siamea*; CE, *Casuarina equisetifolia*; CeP, *Cecropia peltata*; CeO, *Cedrela odorata*; Ceiba, *Ceiba pentandra*; CM, *Celtis mildbraedii*; CEx, *Chlorophora excelsa*; CZ, *Cinnamomum zeylanicum*; CL, *Citrus lemonade*; CN, *C. nobilis*; CS, *C. sinensis*; ClP, *Cleistopholis patens*; CF, *Cnestis ferruginea*; CoN, *Cocos nucifera*; CV, *Codiaeum variegatum*; CG, *Cola gigantea*; CoM, *C. millenii*; CNi, *C. nitida*, CA, *C. acuminate*; CMi, *Cordia millenii*; Cot, *Gossypium* spp; CC, *Crescentea cujete*; DO, *Daniella ogea*; DR, *Delonix regia*; DE, *Duranta erecta*; DG, *Dialium guineense*; DB, *Distemonanthus benthamianus*; DM, *Duboscia macrocarpa*; EG, *Elaeis guineensis*; FEx, *Ficus exasperata*; FSpp, *Ficus* spp; FU, *F. umbellate*; FE, *Funtumia elastic*; GM, *Garcinia mangostanol;* GlS, *Gliricidia sepium*; GA, *Gmelina arborea*; HL, *Hallea ledermannii*, HS, *H. stipulosa*; HB, *Hevea brasiliensis*; HiB, *Hildegardia barteri*; HF, *Holarrhena floribunda*; HyA, *Hymenostegia afzelii*; HA, *Hymenostegia aubrevillei*; JC, *Jatropha curcas*, KC, *Khaya cordifolia*; KS, *K. senegalensis*; LS, *Lagerstroemia speciose*; LaS, *Lannea schimperi*; LW, *L. welwitschii*; L_Spp, *Livingstonia* spp; MB, *Macaranga barteri*; MH, *M. heudelotii*; ME, *Maesopsis eminii*; MA, *Mammea africana*; Mangifera, *Mangifera indica*; MD, *Margaritaria discoidea*; MC, *Michelia champaca*; MT, *Millettia thonningii*; MH, *Millingtonia hortensis*; MM, *Monodora myristica*; ML, *Morinda lucida*; MO, *Moringa oleifera*; MoM, *Morus mesozygia*; MyA, *Myrianthus arboreus*; NL, *Nauclea latifolia*; New_L, *Newbouldia lavis*; OS, *Oncoba spinosa*; PB, *Parkia biglobosa*; PaS, *Parkinsonia speciose*; PP, *Pelthophorum pterocarpum*; PA, *Persea americana*; PC, *Pinus caribaea*; Pip_A, *Piptadeniastrum africanum*; PD, *Pithecellobium dulce*; PS, *P. saman*; PlA, *Plumera alba*; PL, *Polyalthia longifolia*; PO, *P. oliveri*; Pro_A, *Prosopis africana*; PM, *Pseudospondias mombin*; PG, *Psidium guaja*; PsS, *Psydrax subcordata*; PH, *Pteleopsis hylodendron*; PyA, *Pycnanthus angolensis*; RV, *Rauvolfia vomitoria*; RL, *Rothmannia longiflora*; SD, *Samanea dinklagei*; SE, *Solanum erianthum*; SC, *Spathodea campanulata*; SM, *Spondias mombin*; SS, *Sterculia* spp.; TI, *Tamarindus indica*; Tectona, *Tectona grandis*; TeI, *Terminalia ivorensis*; TM, *T. montalis*; TeC, *T. catappa*; TS, *T. superba*; TA, *T. angolensis*; TT, *Tetrapleura tetraptera*; ThC, *Theobroma cacao*; TO, *Thuja orientalis*; TH, *Trichilia heudelotii*; Trip_S, *Triplochiton scleroxylon*; VA, *Vernonia amygdalina*; VoA, *Voacanga africana*. **Green space type**; NF = Natural Forest, HG = Home garden, IC = Institutional Compound.

In appendix A2.1, a gradient can be noticed from core urban (mostly negative dim2 and around the centroid) through peri – urban (around centroid and first part of positive Dim2) to the natural forest (sitting further up the positive Dim2 axis) hence depicting high similarity between core urban (HDUZ) and peri-urban (LDUZ) species composition and moderate similarity between peri-urban and the natural forest. High dissimilarity between the core urban and the natural forest is also obvious (Appendix A2.1). Dimension 2 which represents plant species accounted for 14.3 % of the total variation. The most important deviations along this axis were similar to the species-green space associations alreay described above. Dimension 1 which comprised the green space and urban zone explained 17.6 % of the total variation.

5.3.3 Species abundance distribution model for species co-existence

Analysis using species cumulative plots and Kolmogorov-Smirnov test for normality (natural forest at Owabi: D = 0.158, p=0.010; Core urban (HDUZ): D=0.146, p=0.10; and peri-urban (LDUZ): D=0.167, p=0.010) showed that the tree species abundance distribution in all three zones (core, peri-urban and natural forest) were not normally distributed (Figure 5.4 A &B). For a lognormally distributed data, a plot of cumulative number of species on a probit scale against logarithm of species abundance should yield a straight line. This was not the case for all three sites where a sigmoid curve was always produced.

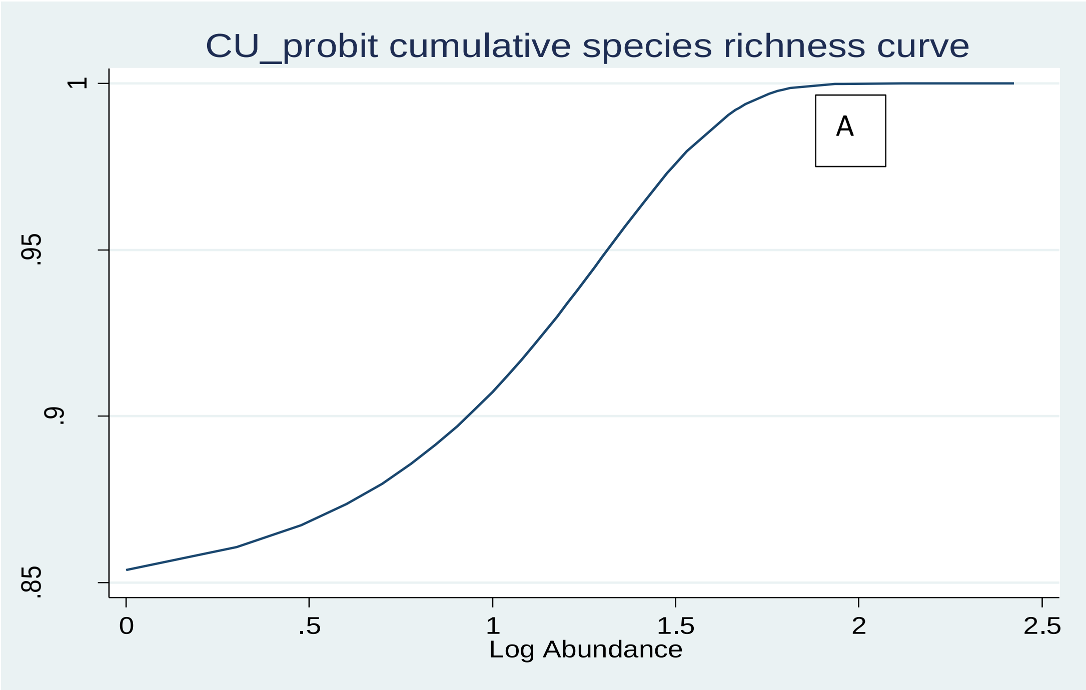
The data were then fitted to two traditional niche models: the Broken-Stick (BS) and Geometric series (GS) models. The GS model always proofed to be a superior model over the null BS model, displaying lower R^2, coefficients of variation (CV) and smaller root mean squares errors (RMSE) (Table 5.4). Hence, the geometric series model best explains the distribution of the species abundances within and immediately around Kumasi. The niche preemption model is a deterministic model which assumes that the resource space (niche) occupied by each species is directly related to the species relative abundance in the assemblage. In other words, the tree diversity of Kumasi is constrained by resource availability and dominated by few (most common) species, which exploit these limited resources at the expense of other species in the community in a declining geometric order according to the respective species relative abundance. For instance, in the LDUZ, *Cassia seamia*, the most abundant species (205 individuals) will consume k amount of the total resource available, Elaeis guineensis, the second most abundant species consumes another k amount from the remaining resources. This geometric sequence of resource exploitation continues until the least abundant species is reached.

Table 5.4 Comparison of Broken-Stick (BS) and geometric series (GS) models using regression. Best fit model in all communities is the GS model: higher R^2, lower CV and RMSE.

	BS: $A = b_0+b_1$LogRank				GS: Log$A = b_0+b_1$Rank				
Community	Equation	RMSE	CV	R^2	Equation	RMSE	CV	R^2	p-value
Whole Kumasi	y=255.16 - 133.96x	32.11	108.50	**0.76**	y=1.926 - 0.016x	0.214	24.0	**0.90**	<0.0001
Peri-Urban (LDUZ[1])	y=123.9 - 66.3x	16.11	108.55	**0.74**	y = 1.628 - 0.016x	0.197	28.5	**0.89**	<0.0001
Core-Urban (HDUZ[1])	y=168.01 - 93.7x	18.96	93.17	**0.80**	y= 1.89 - 0.023x	0.172	23.1	**0.94**	<0.0001
Owabi Santuary	y=65.56 - 35.42x	4.43	43.42	**0.91**	y = 1.57 - 0.019x	0.116	17.5	**0.95**	<0.0001

Statistics: R^2 goodness of fit statistic, RMSE = root mean square error, CV (%) = coefficient of variation, b_0 and b_1 regression coefficients of the intercept and slope respectively, A = species abundance and rank = rank in species abundance. [1]HDUZ - High density urban zone; LDUZ - low density urban zone.

Analysis of the species for possible filters (or factors) regulating the species assemblage was conducted based on life history traits. In both core-urban (HDUZ) and peri-urban (LDUZ) areas, pioneer species were 50 and 45 % in composition, with population (abundance) of 893 and 1,114, respectively (Table 5.5). Non-pioneer light demanders (NPLD) were the second dominant guild type in terms of species richness and abundance. In the natural forest at Owabi sanctuary, pioneer and NPLD populations were equal and each was at least three times greater than the population of shade-bearers. Guild type significantly (χ^2 = 173.1, n = 4, p<0.0001) affected the species abundance distribution across the urban zones in the metropolis (Table 5.5).



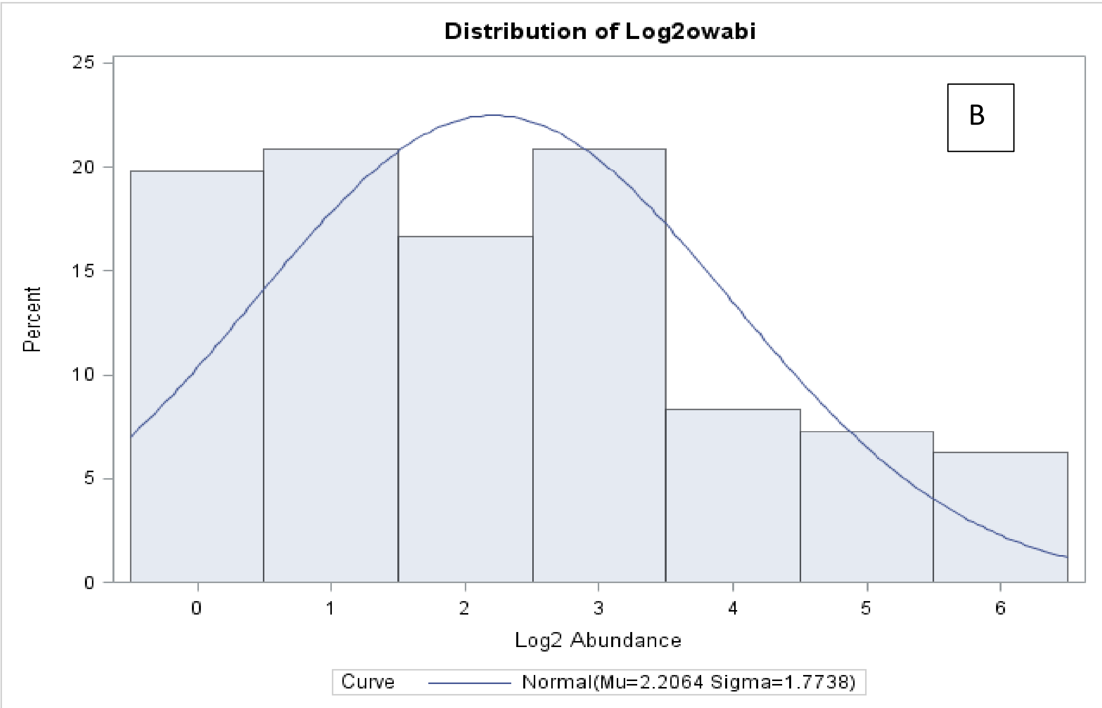


Figure 5.4 Test for normality in species abundance of Kumasi: A) Cumulative plot of species richness on a probit scale B) Lognormal distribution plot for species abundance data for a natural forest in the Owabi sanctuary. The distribution was not significant (D = 0.158, p = 0.010).

Table 5.5 Species abundance for several species guilds across different urban zones. Chi-square test for significant difference: guild types (χ^2 = 173.1, n = 4, p<0.0001), leaf longevity (χ^2 = 108.5, n = 4, p<0.0001) and dispersal mode (χ^2 = 244.6, n = 8, p<0.0001). Species do not overlap in the guild type or leaf longevity but do overlap among dispersal modes.

Traits	Core urban (HDUZ[1])	Peri-Urban (LDUZ[1])	Total urban	Owabi Sanctuary
Guild type				
Pioneers	893	1,114	2,007	405
NPLD[++]	587	378	965	407
Shade-tolerant	251	160	411	130
Leaf longevity				
Deciduous	532	610	1142	307
Evergreen	1,397	1,033	2,430	327
Semi-deciduous	79	63	142	43
Dispersal mode				
Anthropochory	1,752	1,296	3,048	450
Zoochory	885	659	1,544	289
Anemochory	228	344	572	199
Autochory	162	131	293	55
Hydrochory	359	130	489	27

[++]NPLD = non-pioneer light demanders [1]HDUZ - High density urban zone; LDUZ - low density urban zone

Furthermore, chi-square test of effects of mode of species dispersal, an indicator of how species may have arrived in this habitat, revealed significant effects (χ^2 = 244.6, n = 8, p<0.0001). Tree species abundances were not independent of the core urban (HDUZ), peri-urban (LDUZ), and the natural forest zones. Most species abundance was associated with anthropochory, suggesting that human activities account for the presence of most of the tree species in the city. Zoochory and anemochory were the other important contributors to the species pool reiterating the relevance of animals and wind in shaping this plant species assemblage. Similarly, there was a strong association between leaf longevity and the urban zone within the metropolis (χ^2 = 108.5, n=4, p<0.0001). More than two-thirds of the trees in both peri-urban (LDUZ) and core urban (HDUZ) areas were evergreen trees, with the second being deciduous and the rest being semi-deciduous (Table 5.5). The list of species showing origin and guild type is presented in Appendix 1.

5.3.4 UGS tree diversity and function

Figure 5.5 displays a relationship between plant species richness, abundance and UGS carbon stock density in both soil and vegetation. Vegetation carbon density modestly correlated with species richness (r = 0.6962, p = 0.0511) and not species abundance among UGS types. Green spaces with the highest species richness had the most vegetation carbon stock densities whereas those with the lowest species richness had the least carbon densities. Hence, the green space carbon sequesteration potential depends on the number of species in addition to other factors and not the number of individual trees (abundance) per se.

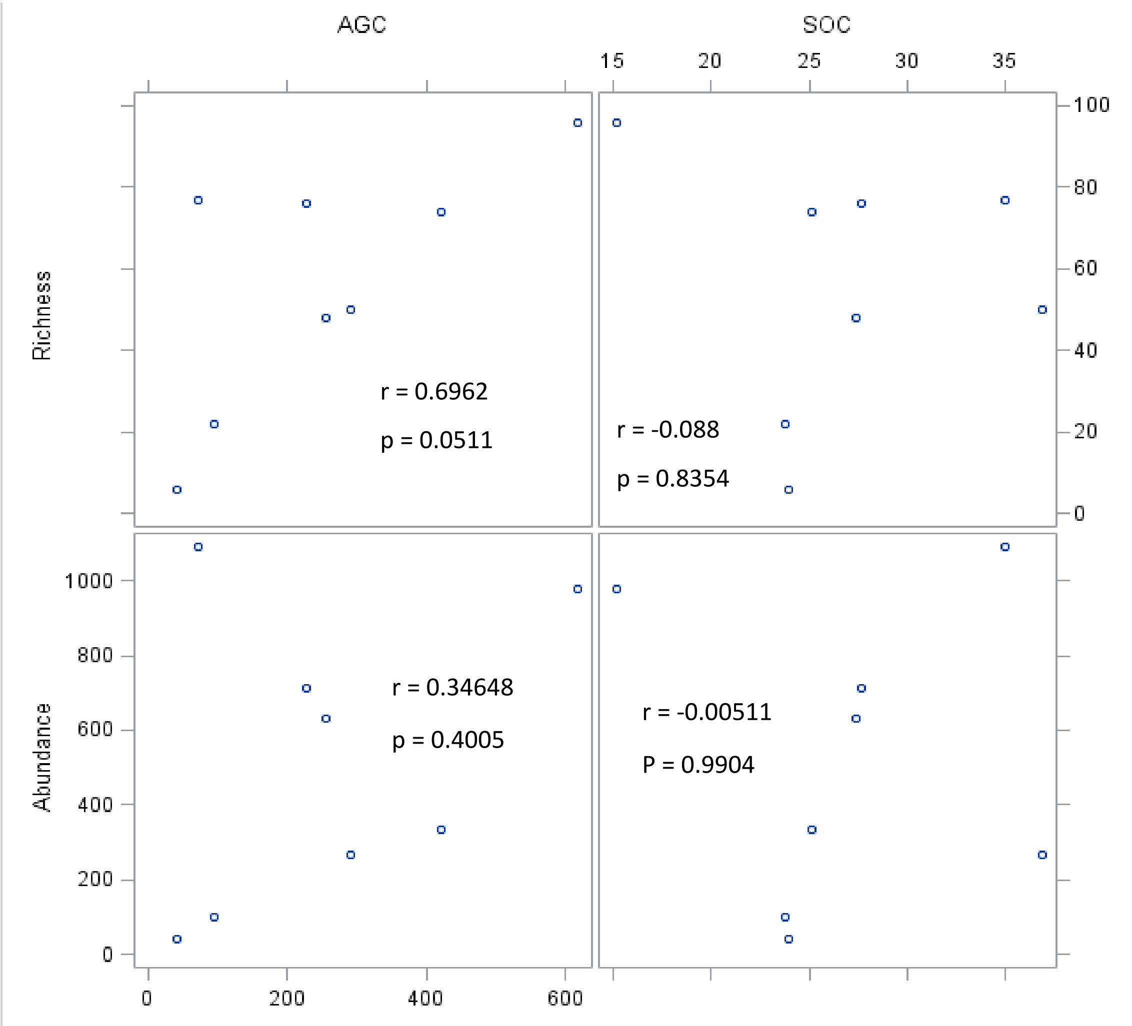


Figure 5.5Pearson correlation between carbon storage density (AGC-aboveground carbon, SOC soil organic carbon (t C/ha) against UGS species richness, species abundance, and tree population density. Species richness significantly correlate with aboveground carbon at alpha = 0.10.

5.3.5 Plant traits and biomass accretion

Factor scores of life history traits of tree species in Kumasi were used to examine the possible traits favoring tree productivity in the city. Six components from our PCA analysis with eigenvalues > 1 and from a scree plot analysis were found to be meaningful. However, based on "cumulative percent of variance accounted for", the first four components accounted for 74.5 % of the variance. Thus, the first four factors were retained.

Life history traits and corresponding factor loadings are presented in Table 5.6. A factor (trait) is said to load on a given component if the factor loading was at least 0.45 for that component and less than 0.45 for the others. On this premise, component 1 which had an Eigenvalue of 4.42 and accounted for 36.8 % of the variance had five significant factor (variable) loadings (traits): native, pioneer, anthropochory, zoochory, and evergreen species. Anemochory and deciduous species significantly loaded component 2, which had an Eigenvalue of 1.96. Component 3, with an Eigenvalue of 1.43 and accounting for 11.9 % of the variance, had exotic and NPLD (non-pioneer light demanders) species as significant factor loadings.

Table 5.6 Rotated factor patterns and factor loadings on principal components. Printed values are multiplied by 100 and rounded to the nearest integer. Values greater than 0.45 are flagged by an '*'.

Guild/Trait	[2]PC1	PC2	PC3	PC4	PC5	PC6
Native	90*	-7	-25	-16	6	-12
Exotic	30	41	72*	29	9	22
Pioneers	86*	33	-1	21	-11	16
NPLD[1]	9	-7	91*	-15	-5	-12
Shade-bearer	6	4	0	- 1	99*	-2
Anthropochory	86*	-3	42	13	15	10
Zoochory	80*	32	20	-17	4	-9
Anemochory	5	94*	1	6	-10	-4
Autochory	2	0	-2	-4	-2	97*
Hydrochory	3	-1	-2	93*	-1	-5
Deciduous	8	92*	4	-8	16	4
Evergreen	86*	-14	41	17	4	8

[1]NPLD = Non-pioneer light demander [2]PC = Principal component

Factor scores generated from PCA analysis of multiple traits discussed apriori were considered as independent variables, while mean tree species carbon and total species abundance were used as dependent variables in multiple regression analysis. The regression of standardized mean tree carbon on component 1 (p=0.02) and component 2 (p=0.025) were statistically significant. Regression of total abundance on component 1 (0.024) was also statistically significant. With respect to mean tree carbon, 30 % of the variation was explained by components 1 and 2 whereas 20 % of the variation in total species abundance was explained by component 1 (Table 5.7). The effect of components 1 and 2 on the former were negative whereas the effect of component 1 on the latter was positive. Therefore, mean tree carbon decreased when species abundance of the following traits: native, pioneer, anthropochory, zoochory, evergreen, anemochory and deciduousness increased. In contrast species abundance increased when native, pioneer, anthropochory, zoochory, and evergreen species populations increased.

Table 5.7 Coefficients of multiple regression of factor scores against mean tree species and total abundance in Kumasi metropolis. p-values in bold are significantly different at alpha (α) = 0.05.

Component	Tree carbon	p-value	R^2	Species abundance	p-value	R^2
Intercept	965.3	**9.32E-06**	**0.30**	25.404	**2.55E-06**	**0.20**
Component 1	-497.5	**0.0209**		11.801	**0.0241**	
Component 2	-475.4	**0.0250**		5.374	0.3032	
Component 3	294.47	0.1719		-4.06	0.4361	
Component 4	279.59	0.1693		-1.08	0.8350	

Component 1 consists of the following species traits; native, pioneer, anthropochory, zoochory, and evergreen, Component 2; anemochory and deciduousness, Component 3; exotic and NPLD, and Component 4; hydrochory.

5.4 Discussion

5.4.1 Species diversity in green spaces and different urban zones

The tree diversity of Kumasi consists of several tree species of native and exotic origins and of various life history traits. Species richness, diversity, and evenness differ widely among UGS types and urban zones. Several UGS are fairly similar in species composition. The most species rich and abundant green spaces being: natural forest, home gardens, institutional compounds, and public parks.

The presence of natural forest, the high proportion (>50%) of native species in the city's species pool, and the low prospects of artificially regenerating many native species, are subtle indications that Kumasi was inherently high in tree diversity prior to being severely urbanized and that the current species assemblage is partly shaped by its geodiversity. Urban biodiversity is often attributed to the inherent and preferential location of cities in biodiversity hotspots (Kühn et al. 2004), socio-ecological factors (Muller et al. 2013; Hope et al. 2003; Kinzig et al. 2005; Cilliers et al. 2013), the varied niches and as safeguard against inadvertent pests and disease outbreaks (Santamour 1990), and human actions through species introduction and landscape heterogeneity (Niemelä 1999; Araújo 2003). Indeed, strong correlations between dense human settlemnets and biodiversity have led to conclusions that conditions attracting humans to cities also attract biodiversity (Balmford et al. 2001; Araújo 2003).

Cemeteries and natural forest share many species (mostly natives) in common but the former are less species rich due to selective preservation of native species e.g. *Morinda lucida*, *Ceiba pentandra*, *Bombax buonopozense, Margariteria discoidea* etc., planting of preferred exotic species *Cassia siamea*, *Gliricidia sepium*, *Mangifera indica* and the need for space for burial. Examination of size and location (urban zones) effects on plant diversity of cemeteries could provide better insights on their overall contribution to the species pool of Kumasi.

Home gardens and institutional compounds in cities signify the proximity and dependence of humans on nature. Their species richness and diversity in Kumasi are similar to the home garden tree species richness, diversity and evenness reported in Rio Claro, Brazil (Eichemberg et al. 2009). High species diversity in home gardens are manifestations of their multifunctional and structural complexities (Agbogidi and Adolor 2013), underpinned by various socio-ecological constraints (Eichemberg et al. 2009: Cilliar et al. 2013). Whereas poorer urbanites maintain small home gardens for provisioning of basic services such as alimentary, medicinal, income, livelihood services which reflect their (urbanites) rural origins and cultural heritage, the relatively wealthier class invest in large home gardens for their aesthetic and recreational functions (Eichemberg et al. 2009; Cilliers et al. 2013). Most species on home gardens and institutional compounds are selectively cultivated or conserved natural regenerations. However, unlike home gardens, species on institutional compounds are primarily maintained by government administrative jurisdictions for their shade and ornamental attributes, boundary demarcations, wind breaks, etc. Species such as *Elaeis guineensis, Mangifera indica, Persea americana, Citrus* species, and *Cocos nucifera* are common home garden trees whilst *Cassia siamea*, *Millettia thornningii*, *Polyalthia* species, *Mangifera indica*, *Citrus* spp., are common on institutional compounds. Home garden ownership and management in developing countries is an attribute of women (Aworinde et al. 2013) but no explicit evidence linking home garden diversity and richness to social class and gender exists at the moment.

Streets and parks contain modest amount of tree diversity in Kumasi and reflect a profound human influence on species richness and diversity, since they are mostly planted. Species richness may be dominated by native species since the best locally adapted species are planted (Richards 1993). In Kumasi trees on streets and parks include both retained natural regenerations of natives and planted exotics. For instance, the KNUST botanical garden consists of cultivated and natural forest zones and harbors about 115 tree species (Anning et al. 2008). Common street and public park tree species include: *Cassia siamea*, *Cedrela odorata*, *Terminalia catappa*, and *Peltophorum pterocarpum* planted mostly because they are fast growers, adapt easily to the urban environment and provide a unique aesthetic value to the cityscape. Exotic tree species commonly found in parks include: *Thuja occidentalis*, *Callistris cupressiformis, Pinus spp.*, imported from the temperate regions for experimental purposes but also perhaps as a legacy of colonialism and present day global migration. Because of limited human use and interference, parks furthest from the city center tend to have higher species richness (Kendal et al. 2012). Although this hypothesis was not explicitly tested in this study, it is possible that the level of control and use, as well as the distance from the city center, in conjunction with other variables might explain inter park disparities in species richness in Kumasi.

Plantations contain modest species richness and diversity because several monocultures of different well adapted species have been cultivated for both individual and group goals. Farms and grasslands have the lowest species richness and diversities because only few economic species are often retained on the farms for their direct or indirect benefits to landowners. Besides, trees are often felled to create space for the agricultural and grazing activities, hence the low tree densities in these green spaces.

Species richness and diversity are significantly higher in the peri-urban (LDUZ) compared to the core urban (HDUZ) area. Proportion of native species increased progressively from the core urban area to the peri-urban and to the neighboring natural forest. These results are congruent with findings by Burton et al. (2005) who noticed a decreasing trend in exotic species composistion, richness and diversity with distance from the urban center due to varying intensity of disturbance. The modified environments in cities and human preference for certain species give non-native species competitive advantage (Knapp and Kühn 2012). In Kumasi, the pattern of exotic/native species distribution in the core, periurban and natural forest may be due to differences in environmental quality (light, heat and pollution), the level of heterogeneity in green cover, and human preferences. In most cities globally, core areas are characterized by low species richness and high number of synanthropes (global homogenizers) whereas the peri-urban habitats are more species rich and dominated by native species (McKinney 2006; McKinney 2008). It is unclear whether Kumasi's non-native tree species can adequately be classified as synanthropes due to the paucity of urban biodiversity data from cities in developing countries in the tropical regions.

5.4.2 Comparison with regional species richness and diversity

The species richness, diversity and guild composition of woody plants in Kumasi are numerically comparable to tree species diversity and composition in other traditional land uses within the country. The tree species richness (176) of Kumasi is greater than the species richness of 66 in a cocoa farm (Anglaaere et al. 2011), 73 in Kakum National Park (Pappoe et al. 2010), 88 in transitional forest located in the Brong-Ahafo region, 70 in the Boabeng Fiama Monkey sanctuary (Kankam et al. 2013) and fairly similar to the 126 and 133 species found in natural forest and fallow lands respectively within the high forest zone of Ghana (Anglaaere et al. 2011) and the 171 species in the Tano Ofin globally significant biodiversity area (GBSA) (Enninful 2013). Urbanization alters both the abiotic environment (e.g. light regime, nutrient supply, moisture levels) and biotic environment (human interferences and changes in predator populations), often creating ambiance and multiple environmental subsets conducive for generalists, synanthropes, and urbanophilic species of both native and exotic origins as well as favoring the best adapted species of different guild compositions (McKinney 2006; McKinney 2008; The Convention on Biological Diversity (CBD) 2012) and consequently promote high beta diversity (Niemelä 1999). Overall, the tree species richness of Kumasi alone accounts for 8 % of the total plant species in the high forest zone (2,100 species) of Ghana. This is far less than what is observed in Concepcion, Chile (Pauchard et al. 2006) which contain at least 50 % of the plant species richness of the country, but significant for conservation considerations.

The proportional composition of the guild types of species in Kumasi portrays the landscape as a degraded habitat. The guild composition of pioneers and non-pioneer light demanders (NPLD) are respectively, 42 and 34 % at Boabeng Fiama sanctuary (Kankam et al. 2013) and 29 and 40 % at the Kakum National Park (Pappoe et al. 2010). The Tano Ofin GBSA, located in a forest reserve within the tropical high forest zone of Ghana, has 46 % of shade bearers (Enninful 2013). Light, a common feature of urban habitats, has been shown to correlate positively with pioneer and stress-tolerant species in cities in China (Zhan et al. 2013; Huang et al. 2013). Hence, the guild composition of Kumasi suggests light was an important filter determining species composition and diversity in the city.

5.4.3 Species abundance distribution and species coexistence

Level of urbanization altered the community assemblage of tree species in Kumasi. In all three urban zones (urban, peri-urban zones, and the natural forest at Owabi sanctuary), the geometric series (GS) model was the best fit to the species abundance distribution. The GS model has been shown to describe many faunal and plant assemblages (Fattorini 2005; Caruso and Migliorini 2006; Do et al. 2014), often depicting early stages of succession or a species-poor environment (Whittaker 1965) or disturbed environments (Caruso and Migliorini 2006). This indicates that a few or a single species exploit a greater proportion of the ecosystems resources relative to their respective relative abundances, leading to resource exhaustion. Considering that light is an important abiotic resource and is readily available in urban areas, it is appropriate that majority of the tree species in Kumasi metropolis are light demanders: either pioneers or non-pioneer light demanders. While the high light levels may have selected for shade-intolerant species, ease of propagation and dispersal ability could have contributed significantly too. Most tree species in Kumasi are dispersed by anthropochory followed by zoochory. Presence of tall buildings and dense compact surfaces in cities, limits the possibility of anemochory (buildings act as barriers) and hydrochory. These results are quite consistent with findings suggesting that urban areas tend to have higher proportion of animal dispersed rather than wind dispersed plants (Knapp et al. 2008a). Urbanization favors plants with high dispersal capacities (Kuhner and Kleyer 2009; Moffatt et al. 2004). By implication, these embody plants with the most viable dispersal agents and which are tolerant to a wide range of environmental conditions. Hence, both biophysical and social factors determine species coexistence in urban landscapes (Pickett et al. 2008). The influence of dispersal limitations and environmental filtering in the tree assemblage of Kumasi is premonition that tree species distribution of Kumasi may be founded on both niche-based and neutral-based theories (López-Martínez et al. 2013). It would be interesting to pry into the applicability of this latter theory in urban landscapes.

5.4.4 Urban green space diversity and function

Tree species richness of green spacea is correlated with mean green space aboveground carbon density but unrelated to the mean soil C densities of UGS within Kumasi metropolis. Since Darwin's diversity-productivity postulates, several investigations have upheld the consensus that increasing ecosystem diversity corresponds with increased ecosystem functioning or processes (Naeem et al. 1994; Hector 1999; Chapin et al. 2000b; Reich et al. 2001; Cardinale et al. 2011). Higher primary productivity (carbon storage/sequestration) in mixed species communities compared to monocultures have been reported in several experimental and observational studies (Tilman 2001; Cardinale et al. 2007; Nero 2009; Reich et al. 2001; Bezemer and Van Der

Putten 2007). Such diversity related increases in primary productivity is attributed to species selection effects, species complementarity, facilitation, and niche differentiation (Hillerislambers et al. 2012; Hector 1999; Tilman 2001; Cardinale et al. 2007). Tree species richness and productivity relations in the green spaces in Kumasi can possibly be attributed tp a combination of species selection and niche differentiation effects as well as other confounding factors. Species in the natural forest and public parks are of several different guild types suggesting that these species are exploiting different parts of the resource space in order to coexist. Yet in several other green spaces, species are selectd preferentially for specific desired services they confer on society. Evidence of selection effect is apparent when the mean biomass of the most productive species exceeds the mean biomass of the entire community or green space (Cardinale et al. 2007). This however, was not categorically tested in the current study. The positive richness-productivity relationship among tree species of green spaces in Kumasi reiterates the importance of adopting mixed species afforestation programs for the purposes of enhacing urban sustainability. The findings provide partial evidence supporting the richness-productivity research gap highlighted in Cardinale et al. (2011).

The results further reveal the importance of life history traits of tree species on biomass accretion and species abundance in the metropolis. Decrease in carbon storage per tree in each principal components imply plant traits loading each principal component are interacting antagonistically. Due to ease of dispersal (anthropochoric and zoochoric dispersal habits), native pioneer species are more abundant in the city. However, their relatively fast growing habit coupled with their relatively shorter lifespans have profound influence on tree size and wood density and hence compromise biomass accretion. Evergreen species have trade-off of investing more energy and resources in defense rather than on growth (photosynthesis) (Santiago and Wright 2007) which further compromises aboveground carbon storage. Similarly, deciduousness which is often associated with high photosynthetic assimilation rates (Santiago and Wright 2007) may have been negatively affected by wind dispersal, an attribute heavily impeded in cities because of the buildings and pavements. Species origin and guild types (light requirements, dispersal mechanisms, and leaf life span) contributed enormously to carbon storage in trees in the metropolis. The findings here do not quite agree with conclusive assertions that high functional groups/trait diversity in a community, which is often linked to species richness, contributes more to ecosystem functioning/processes (Tilman 2001; Hector 1999; Roscher et al. 2012). Plant trait variations in cities and their surrounding neighborhoods are quite thoroughly studied (Albrecht and Haider 2013) but little is known about how urban plant traits influence productivity (ecosystem service provisioning) let alone life history trait effects on carbon storage (ecosystem services delivery in general). It is also worth noting that many studies linking plant traits to ecosystem productivity were experiments conducted on grasslands. It is therefore appealing to conduct experimental studies on urban plant (tree) species/trait effects on ecosystem services delivery in cities in developing countries, where most urbanization is currently taking place.

5.4.5 Ecological importance of urban tree diversity

Aside from harboring a chunk of native tree species, the flora of Kumasi metropolis includes some 14 tree species listed as vulnerable or near threatened in the IUCN database. From literature survey, many tree species of the metropolis were multipurpose in attributes, at least in their native ranges. Nearly all tree species are a source of food, shade, fuel and medicine. Many other species are known for the provision of timber, ornamental services, tannins, essential oils, handicrafts, gum, fodder, soil amendments, and habitats for fauna. These together highlight the conservation significance of the urban ecosystem. Hence, governments and private enterprises in developing countries ought to intensify conservation interest in urban ecosystems and biodiversity. In Ghana, like many other African countries, a clear policy guideline for biodiversity conservation in cities is necessary to foster better conservation efforts in the country.

5.5 Conclusion

This study explores tree species diversity of a developing country city, uncovers a fundamental theory behind its tree species assemblage, and wades into the urban biodiversity-ecosystem productivity discourse. Relatively high species richness fortified by both native and alien species of nearly equal proportions occur in Kumasi metropolis. Globalization, profound human activity, and the unique ambience of the metropolis collectively foster higher non-native species in the core urban area compared to the peri-urban and surrounding urban fringes. Further urbanization processes in the city could increase the amount and proportion of non-native species especially in the peri-urban zone. The parity of species richness between this metropolis and some national parks, biosphere and forest reserves of global significance in the country, reiterates the need to wholistically prioritize and conserve urban ecosystems. In particular, conservation efforts should target the natural forest, home gardens, institutional compounds, and public parks, which are high in species richness and contain some important but vulnerable native species.

The geometric series model best fitted the tree species assembly data in both the core urban (HDUZ) and peri-urban (LDUZ) zones, depicting an environmentally impoverished community. It is inferred that species abundance and distribution is limited by the niche space/resource availability. In other words, anthropogenic disturbances in the environmental regime (i.e. high light) and in the dispersal and propagation of species (anthropochoric dispersal) whether deliberate or accidental, may have contributed to shape the species assemblage and pool of this metropolis. It is concluded that Kumasi's tree diversity and species community assemblage is a result of its geodiversity, disparate socio-economic interests, and the prevalence of few or limited environmental or abiotic conditions.

Tree species richness of UGS positively correlated with mean carbon stock density for each green space type whereas clusters of life history traits negatively correlated with mean carbon per tree species. These findings are in partial agreement with species diversity-productivity (function/process) and functional group-productivity theses. It is concluded that species richness and species life history traits determine ecosystem productivity at the stand and tree level, respectively. To harness greater benefits from urban ecosystems, mixed species afforestation is recommended in urban areas across developing countries. Experimental manipulations of tree species richness and functional groups/traits effects on ecosystem processes/function in the urban settings are crucial in solidifying the aforementioned arguments. The impacts of exotic species on overall ecosystem processes and service delivery require further investigation. Response of urban plant species/traits to the dynamics of urban environmental conditions (i.e. temperature and moisture regimes) remain interesting research gaps in developing country cities and so is testing the validity of more models fitting urban tree species assemblages.

6 GENERAL CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

Urban green spaces (UGS) are an emerging force in redressing contemporary local environmental change concerns. They are not only the immediate contact with nature for the greater majority of the world's population, they are also a priceless source of a wide range of ecosystem services and are essential to reducing the ecological footprint of cities (Gómez-Baggethun and Barton 2013; Bolund and Hunhammer 1999; Tzoulas et al. 2007; Cilliers et al. 2013; Coutts and Hahn 2015). In particular, UGS can directly minimize urban climate change related hazards such as urban heat island effects, flash floods, and air pollution through evaporative cooling, shading from trees, directly removing CO_2 from the atmosphere, and filtering air pollutants. They are also a rich preserve of biological diversity upon which all ESS emanate. While well integrated into urban landscape planning in developed countries, in cities in developing countries UGS are hardly planned for and are outcompeted by housing and other grey infrastructure projects. Beside the uncertainties in the magnitude of green cover in cities, inequities in their distribution is rapidly metamorphosing into issues of environmental injustices. Furthermore, the contributions of UGS to biodiversity conservation and climate change mitigation and adaptation are not thoroughly investigated, despite their high potential. Hence, this study was initiated to partially address these voids using Kumasi, Ghana as a case study.

The **general** objective was to assess the extent of green cover in an African city and its biodiversity and climate change mitigation values/potential.

This study broadly concludes that cities in developing countries can contain a substantial amount of green space cover with high biological diversity values and provide key ecosystem functions/services, particularly mitigating and adapting to climate change. The area of Kumasi considered in this study is about 45-50 % green: 2/3 of which is covered with trees. The green cover contains 176 tree species and stores up to 3,758 Gg C. Hence, maintaining adequate green space cover in cities in developing countries can contribute appreciably to mitigate climate change effects and biodiversity loss as well as provide essential ecosystem services such as food and health gains.

However, the uneven distribution of green cover in Kumasi could precipitate into environmental/distributional injustice.

One specific objective of this study was to examine spatio-temporal dynamics of green spaces in relation to socio-economic wellbeing of urbanites in Kumasi. Green space distribution in the city is not only uneven and slightly unrelated to the socio-economic patterns of submetropolis; UGS are in a state of tremendous decline with time and population increase. At the current rate of decline, Kumasi could loose almost all the green cover to buildings and other grey infrastructure within the next ten years. This would compromise the achievement of SDG 11.7 and the attainment of the recommended WHO and UN per capita green space area requirements in the metropolis. So far, the coarse scale of submetropolis obscures any glaring correlations between the socio-economic variables of inhabitants and green space cover of the city. Perhaps, a detailed study at the fine scale of neighborhood should reinforce the confidence in this hypothesis. UGS distribution in Kumasi is, however, uneven among submetropolises and could precipitate into environmental injustices. This is compounded by the fact that the character (extent, species composition and type) of green spaces varies widely in the city. Considering the multifaceted environmental problems of cities, it is important urban policy recognizes and integrates private green spaces into urban planning process. Efforts at ensuring uniformity in green space distribution and in protecting sensitive ecological risk averse areas within the city should encompass both public and private green spaces. This entails, substituting unpaved and paved bare surfaces in the city with living green surfaces.

Another objective of this study was to examine carbon sequestration patterns of green spaces in the metropolis. It is concluded that the carbon storage in the city depends on the type of green space. Tree dominated green spaces (parks and natural forest with limited human interference) sequestered more carbon in aboveground vegetation whereas green spaces closely associated with built-up areas (home gardens, plantations and trees on institutional compounds) stored more carbon belowground. The core urban area also tended to store less carbon compared to the periurban fringes. Soil C was the most relevant C pool in grass and farmlands. Greening bare areas with grass and trees and planting trees and lawns along streets could greatly enhance the carbon stocks of the metropolis. The outer regions (LDUZ) had more carbon than the core (HDUZ) of the metropolis. Hence, greening the HDUZ area without compromising the stocks in outer edges should be a major priority of the city authorities. Readjusting existing municipal housing and land acquisition policies in Ghana and in Africa to by default include trees in house compounds and around houses can foster greener cities and enhance carbon sequestration. Deliberately maintaining a swath of vegetation around the peri-urban fringes to serve as an ecotone between rural and urban ecosystems can massively boost the urban biodiversity and ecosystem functions.

The final specific objective of this study was to analyze the diversity, composition, coexistence, and diversity-productivity relations of tree species and life history traits of green spaces in Kumasi. Here, the study concludes that tree species diversity and distribution depend on the type of green space and portrays a perturbed landscape in early seres of succession with the overall ecosystem productivity sustained by both species and life history trait diversities. In other words, the tree diversity of cities can be very high: higher than some natural forest and agricultural landscapes in this region. Natural forest, home gardens, institutional compounds, public parks, have the highest species richness and diversity indices. Streets, cemeteries, and plantations had moderate species richness while farmlands and rangelands within the city had the lowest richness values. The core (HDUZ) urban area was less species rich compared to the outer peri-urban zone (LDUZ). However, the reverse was true when exotic species richness was considered. Furthermore, the geometric series model best fitted the tree species assembly data in both these zones and in the neighboring natural forest, depicting an environmentally and species impoverished community. It is inferred that species abundance and distribution is limited by the niche space/resource availability. In congruence with the niche partitioning hypothesis, majority of the species were pioneers and non-pioneer light demanders, indicating that light (abiotic factors) regulates the species assemblage of Kumasi. Similarly, most species although exhibit other modes of dispersal have the tendency to dispersed by humans (anthropochory), thus, reavowing the importance of society in shaping the species assemblages of cities.

The unique diversity of Kumasi, agrees with previous studies asserting that urbanization tends to select for species with traits adaptable to unique environmental conditions. Furthermore, it reiterates the significance of high species and trait diversity in boosting ecosystem productivity, since UGS species richness correlated strongly with UGS carbon storage and life history traits of species with tree biomass carbon. By maintaining high tree diversity, there is high certainty of increasing tree productivity and diversifying the kinds and amount of ecosystem services that green spaces can offer. A burgeoning question is how do we increase plant/tree diversity in cities?

Urban ecological studies, especially in relation to UGS tree species and trait diversity to the ecosystem services they provide, are scanty and not well grounded. Therefore, it is important to conduct similar studies in other cities in Africa and in other developing countries in order to capture climatic and socioeconomic differences and impacts on green space cover and the ecosystem services they provide. Besides, climate change and pollution mitigation, green spaces offer many other services for human wellbeing. An interesting and long over looked research gap is linking green space and plant diversity to the specific services they provide. How biodiversity and ecosystem services generated within the city mitigate regional and global biodiversity loss and augments ecosystem service supply from landscapes in the surrounding hinterlands are exciting fields that remain understudied. It is equally important to find creative ways to improve urban biodiversity and boost ecosystem service supply. Pollution impacts on urban ecosystem health within developing countries could be an equally exciting field of study. Finally, it is anticipated that as we transition to a more urban society, green spaces will be become more central to sustainable urbanism, triggering a variety of research interests and uniting man with nature.

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8 APPENDICES

Table A1. 1 Species, Families, Guilds, Abundance, diameter at breast height (dbh, cm), Height (Ht, m) wood density (WD) aboveground carbon (AGC, kg) and belowground root carbon (BGC, kg). NPLD – non-pioneer light demander; ST – shade-tolerant.

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh (cm)	Ht (m)	WD	AGC (kg)	BGC (kg)
Fabaceae- Mimosoideae	*Acacia senegal*	Exotic	Pioneer	22	22	36	25.4	17.6	0.57	209.1	34.4
Euphorbiaceae	*Acalypha sonderiana*	Exotic	NPLD	1	1						
Bombacaceae	*Adansonia digitate*	native	Pioneer	1	1	1	156.6	20.8	0.17	2102.9	274.5
Fabaceae - Mimosoideae	*Adenanthera pavonina*	Exotic	Pioneer	1	1	3	22.5	15.2	0.85	221.0	35.6
Fabaceae – Caesalpinioideae	*Afzelia africana*	Native	NPLD	2	2	1	87.5	28.3	0.57	1656.2	222.3
Fabaceae - Mimosoideae	*Albizia adianthifolia*	Native	Pioneer	17	24	13	45.2	22.1	0.48	881.6	119.6
Fabaceae - Mimosoideae	*Albizia ferruginea*	Native	NPLD	2	5	3	55.8	16.3	0.71	907.1	129.9
Fabaceae - Mimosoideae	*Albizia lebbeck*	Exotic	Pioneer	17	17	21	23.8	13.0	0.66	143.4	24.9
Fabaceae - Mimosoideae	*Albizia zygia*	Native	NPLD	11	35	9	42.9	16.2	0.53	703.0	99.3
Euphorbiaceae	*Alchonia cordifolia*	Native	Pioneer	1	5	1	11.0	0.0	0.64	24.5	5.4
Apocynaceae	*Alstonia boonei*	Native	Pioneer	24	44	29	46.3	10.5	0.30	467.9	65.3
Fabaceae – Papilionoideae	*Amphimas pterocarpoides*	Native	NPLD	5	13	5	120.7	22.4	0.62	6902.0	777.3
Anacardiaceae	*Anacardium occidentale*	Exotic	Pioneer	3	3	3	24.6	4.9	0.60	51.3	10.1
Annonaceae	*Annona muricata*	Exotic	NPLD	34	34	43	15.1	7.0	0.64	33.1	6.8
Annonaceae	*Annona squamosal*	Exotic	NPLD	11	11	12	12.6	6.4	0.64	22.1	4.7
Gentianaceae	*Anthocleista nobilis*	Native	Pioneer	2	2	2	73.9	0.0	0.50	2578.7	327.3
Gentianaceae	*Anthocleista vogelii*	Native	Pioneer	3	3	3	15.6	14.0	0.50	74.2	13.4
Moraceae	*Antiaris africana*	Native	NPLD	2	2	1	154.8	41.7	0.52	12082.3	1286.7
Moraceae	*Antiaris toxicaria*	Native	NPLD	3	19	3	97.6	24.6	0.52	2895.4	360.1
Araucariaceae	*Araucaria columnaris*	Exotic	Pioneer	4	4	4	20.0	9.1	0.44	45.3	9.2
Moraceae	*Artocarpus incises*	Exotic	NPLD	1	1	2	35.3	11.1	0.53	239.9	38.9

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh (cm)	Ht (m)	WD	AGC (kg)	BGC (kg)
Meliacea	*Azadirachta indica*	Exotic	Pioneer	30	30	28	60.2	15.7	0.69	1249.5	166.9
Poaceae	*Bambusa vulgaris*	Exotic		317	323	45	7.9	4.8	0.00	32.1	6.8
Leguminosae	*Baphia nitida*	Native	ST	4	20	8	12.6	3.1	0.56	28.3	5.9
Leguminosae	*Baphia pubescens*	Native	Pioneer	1	4	1	19.1	24.5	0.63	145.8	26.0
Leguminosae	*Baphia spp.*			1	1	2	21.1	15.6	0.60	109.1	20.1
Clusiaceae	*Allanblankia parviflora*	Native	ST	2	2						
Fabaceae – Caesalpinioideae	*Bauhinia tomentosa*	Exotic	NPLD	6	6	10	18.2	13.2	0.60	70.4	13.5
Sapindaceae	*Blighia sapida*	native	NPLD	39	62	42	54.6	15.4	0.76	1218.1	159.8
Bombacaceae	*Bombax buonopozense*	Native	Pioneer	12	14	12	97.4	24.1	0.32	2358.7	291.3
Asclepiadaceae	*Calotropis procera*	Native	Pioneer	3	3						
Cupressaceae	*Callitris cupressiformis*	Exotic		2	2	2	76.9	12.6	0.48	2013.6	262.5
Annonaceae	*Cananga odorata*	Exotic	Pioneer	9	9	10	24.5	8.9	0.50	75.1	14.2
Meliacea	*Carapa procera*	Native	ST	13	16	13	19.3	15.4	0.60	106.7	19.1
Fabaceae	*Cassia nodossa*	Exotic	Pioneer	1	1	1	21.3	0.0	0.63	138.0	24.7
Fabaceae	*Cassia siamea*	Exotic	Pioneer	337	395	445	27.8	15.6	0.63	248.8	39.7
Casuarinaceae	*Casuarina equisetifolia*	Exotic	Pioneer	31	31	42	25.3	15.7	0.83	260.4	41.9
Cecropiaceae	*Cecropia peltata*	Exotic	Pioneer	1	1						
Meliacea	*Cedrela odorata*	Exotic	Pioneer	77	141	80	76.2	23.1	0.38	1805.8	229.3
Bombacaceae	*Ceiba pentandra*	Exotic	Pioneer	27	45	28	96.6	24.0	0.32	2938.9	342.2
Ulmaceae	*Celtis mildbraedii*	Native	ST	1	25	1	9.8	16.2	0.68	28.5	6.1
Moraceae	*Chlorophora excelsa*	Native	Pioneer	11	21	13	57.6	20.0	0.54	1904.7	230.9
Sapotaceae	*Chrysophyllum perpulcrum*	Native	NPLD	1	1						
Lauraceae	*Cinnamomum zeylanicum*	Exotic	ST	2	2	4	30.7	7.3	0.43	237.9	37.5
Rutaceae	*Citrus lemonade*	Exotic	NPLD	3	3	3	10.1	5.3	0.59	9.1	2.2

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh cm	Ht m	WD	AGC (kg)	BGC (kg)
Rutaceae	*Citrus sinensis*	Exotic	NPLD	107	107	157	15.0	4.8	0.59	36.6	7.3
Annonaceae	*Cleistopholis patens*	Native	Pioneer	1	3	2	18.1	14.0	0.36	45.8	9.3
Connaraceae	*Cnestis ferruginea*	Native	Pioneer	2	2	2	47.5	15.1	0.25	443.7	69.1
Arecaceae	*Cocos nucifera*	Exotic	Pioneer	82	82	70	17.2	11.4	0.00	240.1	40.7
Euphorbiaceae	*Codiaeum variegatum*	Exotic	NPLD	1	1						
Sterculiaceae	*Cola gigantea*	Native	NPLD	6	22	6	74.8	13.1	0.48	2249.1	271.6
Sterculiaceae	*Cola millenii*	Native	NPLD	1	1						
Sterculiaceae	*Cola nitida*	Native	ST	4	6	4	31.4	13.8	0.58	220.7	36.9
Boraginaceae	*Cordia millenii*	Native	Pioneer	2	2	3	18.3	7.5	0.53	44.1	8.7
Malvaceae	*Gossypium hirsutum*			8	8						
Bignoniaceae	*Crescentia cujete*	Exotic	Pioneer	3	3	9	24.1	8.0	0.70	106.8	18.9
Fabaceae – Caesalpinioideae	*Daniellia ogea*	native	Pioneer	1	2	1	44.7	0.0	0.51	751.2	110.5
Fabaceae – Caesalpinioideae	*Delonix regia*	Exotic	Pioneer	98	98	142	39.0	12.7	0.49	386.2	56.7
Fabaceae – Caesalpinioideae	*Dialium guineense*	Native	Pioneer	3	3	5	42.6	6.0	0.79	1142.4	155.3
Fabaceae	*Distemonanthus benthamianus*	Native	Pioneer	1	2	1	162.0	0.0	0.67	19471.0	1961.5
Malvacea	*Duboscia macrocarpa*	Native		1	1	1	8.4	0.0	0.52	9.7	2.4
Verbenaceae	*Duranta erecta*	Exotic	NPLD	1	1						
Arecaceae	*Elaeis guineensis*	Native	Pioneer	424	487	354	17.5	0.0	0.63	82.9	15.8
Meliacea	*Entandrophragma angolense*	Native	NPLD	7	4	1	79.1	27.6	0.63	3788.7	434.7
Meliacea	*Entandrophragma candollei*	Native	NPLD	1	18	5	24.3	0.0	0.63	196.4	33.8
Meliacea	*Entandrophragma utile*	Native	ST	3	1	2	17.8	6.5	0.27	15.3	3.5
Fabaceae	*Erythrina spp*	Native		1	1	1	17.8	6.5	0.27	15.3	3.5
Myrtaceae	*Eucalyptus spp*	Exotic	NPLD	16	18	16	40.8	23.8	0.56	809.7	112.9

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh (cm)	Ht (m)	WD	AGC (kg)	BGC (kg)
Moraceae	*Ficus umbellata*	Native		2	2	3	81.2	24.5	0.40	1744.8	228.4
Apocynaceae	*Funtumia elastic*	Native	NPLD	1	54						
Clusiaceae	*Garcinia mangostana*	Exotic	ST	4	8	5	22.5	7.6	0.81	78.9	15.1
Fabaceae – Papilionoideae	*Gliricidia sepium*	Exotic	Pioneer	14	14	13	20.4	9.2	0.62	112.4	18.9
Verbenaceae	*Gmelina arborea*	Exotic	NPLD	76	77	91	38.7	15.0	0.48	387.2	58.4
Rubiaceae	*Hallea ledermannii*	Native	Pioneer	3	3	3	38.2	0.0	0.53	584.3	87.8
Myrtaceae	*Syzygium jambos(Eugenia jambos)*	Exotic	Pioneer	2	2	7	16.0	10.7	0.65	51.1	10.1
Rubiaceae	*Hallea stipulosa*	Native	Pioneer	2	2	2	13.3	2.9	0.47	34.5	7.3
Euphorbiaceae	*Hevea brasiliensis*	Exotic	Pioneer	22	22	21	27.8	15.4	0.57	306.4	46.3
Malvaceae	*Hildegardia barteri*	Native	Pioneer	6	3	4	68.3	18.1	0.55	655.1	97.3
Apocynaceae	*Holarrhena floribunda*	Native	Pioneer	5	5	1	56.0	31.9	0.54	1325.2	182.5
Euphorbiaceae	*Hura crepitans*	Exotic	ST	1	6	5	66.2	8.9	0.37	1031.5	141.0
Leguminosae	*Hymenostegia afzelii*	Native	ST	1	2	1	75.1	29.3	0.74	2925.0	367.4
Leguminosae	*Hymenostegia aubrevillei*	Native	ST	1	1	1	71.2	28.8	0.82	2903.0	365.0
Verbenaceae	*Jatropha curcas*	Exotic	Pioneer	4	4						
Acanthaceae	*Justicia spp*	Exotic		1	1	1	31.8	10.2	0.40	108.8	20.0
Meliaceae	*Khaya grandifolia*	Native	NPLD	1	1	6	26.1	16.5	0.53	173.0	29.5
Meliaceae	*Khaya senegalensis*	Native	NPLD	10	10	6	77.3	22.4	0.66	2599.5	321.7
Lythraceae	*Lagerstoemia speciosa*	Exotic	Pioneer	21	21	32	39.0	14.2	0.53	454.1	66.8
Anacardiaceae	*Lannea schimperi*	Native		2	2	2	24.4	0.0	0.47	208.2	33.9
Anacardiaceae	*Lannea welwitschii*	Native	Pioneer	1	8	1	66.0	0.0	0.45	1736.0	231.7
Arecaceae	*Livingstonia spp*	Exotic	NPLD	4	4	4	0.0	6.2	0.00	23.6	5.2
Euphorbiaceae	*Macaranga barteri*	Native	Pioneer	1	1	1	47.3	16.2	0.40	367.7	58.8
Euphorbiaceae	*Macaranga heudelotii*	Native	pioneer	2	2	4	16.3	6.2	0.40	23.8	5.0

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh cm	Ht m	WD	AGC (kg)	BGC (kg)
Malvaceae	*Mammea africana*	Native	ST	2	2	3	44.0	17.5	0.78	899.1	125.2
Anacardiaceae	*Mangifera indica*	Exotic	NPLD	229	229	365	34.6	10.1	0.52	255.9	39.8
Euphorbiaceae	*Margaritaria discoidea*	Native	Pioneer	12	15	19	30.1	9.6	0.65	220.9	35.8
Magnoliaceae	*Michelia champaca*	Exotic	NPLD	2	2	2	45.3	11.1	0.51	315.2	50.7
Leguminosae	*Millettia thonningii*	Native	ST	102	102	194	19.1	10.7	0.74	106.3	18.4
Bignoniaceae	*Millingtonia hortensis*	Exotic	NPLD	1	1	9	27.4	17.7	0.49	176.6	30.4
Anacardiaceae	*Monodora myristica*	Native	ST	5	5	7	45.4	1.6	0.58	1244.2	157.1
Rubiaceae	*Morinda lucida*	Native	Pioneer	79	80	68	35.1	11.1	0.64	582.1	79.6
Moringaceae	*Moringa oleifera*	Exotic	Pioneer	25	25	34	13.0	7.5	0.60	30.7	6.0
Moraceae	*Morus mesozygia*	Exotic	Pioneer	1	5	2	63.0	0.0	0.78	589.5	86.8
Cecropiaceae	*Myrianthus arboreus*	Native	Pioneer	1	14	3	9.0	6.7	0.51	7.8	2.0
Rubiaceae	*Nauclea latifolia*	Native	Pioneer	10	10	19	27.3	11.6	0.63	181.5	30.3
Bignoniaceae	*Newbouldia laevis*	Native	Pioneer	17	24	14	29.0	13.5	0.47	214.9	34.8
Salicaceae	*Oncoba spinosa*	Exotic	Pioneer	2	2	2	107.3	23.0	0.64	2276.5	278.0
Fabaceae	*Pakia biglobosa*	Native	NPLD	4	4	5	62.8	10.3	0.54	1277.4	171.2
Fabaceae - Caesalpinioideae	*Parkinsonia aculeata*	Exotic	Pioneer	1	1	2	27.9	12.3	0.40	139.3	23.6
Fabaceae – Caesalpinioideae	*Pelthophorum pterocarpum*	Exotic	Pioneer	107	107	178	37.2	16.7	0.62	558.3	79.0
Lauraceae	*Persea americana*	Exotic	ST	115	115	149	30.4	11.2	0.56	196.3	32.1
Pinaceae	*Pinus caribaea*	Exotic	Pioneer	14	14	16	47.2	20.5	0.48	721.3	104.0
Fagaceae	*Piptadeniastrum africanum*	Native	NPLD	3	44	3	76.4	30.2	0.62	4957.1	550.5
Fabaceae - Mimosoideae	*Pithecellobium dulce*	Exotic	NPLD	75	75	103	25.3	13.5	0.59	188.8	30.7
Leguminosae	*Pithecellobium saman*	Exotic	Pioneer	58	58	77	88.3	17.3	0.48	1852.3	239.2
Apocynaceae	*Plumera alba*	Exotic	NPLD	2	2	2	31.2	8.5	0.43	93.0	17.5
Annonaceae	*Polyalthia longifolia*	Exotic	NPLD	71	63	55	29.8	11.9	0.54	198.4	32.7

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh cm	Ht m	WD	AGC (kg)	BGC (kg)
Fabaceae - Mimosoideae	*Prosopis africana*	Native	Pioneer	21	21	22	22.9	14.0	0.60	152.5	25.7
Anacardiaceae	*Pseudospondias mombin*			2	2	2	26.1	0.0	0.64	240.6	40.4
Myrtaceae	*Psidium guajava*	Exotic	ST	20	20	12	13.5	6.4	0.63	39.0	7.4
Rubiaceae	*Psydrax subcordata*	Native	Pioneer	3	3	6	18.5	3.2	0.63	96.6	18.0
Combretaceae	*Pteleopsis hylodendron*	Native	NPLD	1	1						
Myristicaceae	*Pycnanthus angolensis*	Native	NPLD	1	38	1	14.3	0.0	0.65	50.1	10.1
Apocynaceae	*Rauvolfia vomitoria*	Native	Pioneer	8	9	9	17.3	3.2	0.47	96.7	15.7
Rubiaceae	*Rothmannia longiflora*	Native		1	1	3	10.9	13.2	0.64	27.3	5.9
Leguminosae	*Samanea dinklagei*	Native		1	1	2	32.4	0.0	0.60	481.6	72.3
Solanaceae	*Solanum erianthum*	Exotic	Pioneer	6	6	2	21.6	8.8	0.57	61.3	11.7
Bignoniaceae	*Spathodea campanulata*	Native	Pioneer	14	14	13	48.3	20.9	0.41	770.9	107.4
Anacardiaceae	*Spondias mombin*	Exotic	Pioneer	3	3	2	122.4	35.2	0.72	8846.6	976.9
Malvaceae	*Sterculia tragacantha*	Native	NPLD	4	14	4	58.5	16.0	0.75	3073.4	346.7
Bignoniaceae	*Tabebuia chrysantha*	Exotic	Pioneer	3	3	1	17.0	19.4	0.75	110.1	20.3
Fabaceae – Caesalpinioideae	*Tamarindus indica*	Exotic	Pioneer	5	5	1	61.5	15.3	0.75	1072.9	151.5
Verbenaceae	*Tectona grandis*	Exotic	Pioneer	221	221	263	21.1	13.8	0.60	139.0	23.5
Combretaceae	*Terminalia catappa*	Exotic	Pioneer	76	76	83	39.2	16.0	0.52	474.1	69.0
Combretaceae	*Terminalia ivorensis*	Native	Pioneer	8	19	6	48.5	20.1	0.55	1017.9	135.5
Combretaceae	*Terminalia montalis*	Exotic	Pioneer	32	32	44	28.3	12.7	0.54	178.9	29.6
Combretaceae	*Terminalia superba*	Native	Pioneer	12	43	21	37.6	14.1	0.56	511.6	71.5
Fabaceae	*Tetrapleura tetraptera*	Native	Pioneer	1	2	1	35.8	11.5	0.50	189.9	32.8
Malvaceae	*Theobroma cacao*	Exotic	NPLD	98	98	120	12.0	6.2	0.42	14.2	3.0
Cupressaceae	*Thuja occidentalis*	Exotic	NPLD	1	1	1	21.6	8.0	0.83	81.5	15.5
Meliacea	*Trichilia heudelotii*	Native	NPLD	2	2						
Sterculiaceae	*Triplochiton scleroxylon*	Native	Pioneer	10	64	10	80.5	20.8	0.33	1751.0	225.6

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh cm	Ht m	WD	AGC (kg)	BGC (kg)
Arecaceae	*Neodypsis decaryi*	Exotic	NPLD	1	1	1	43.0	15.5	0.55	398.6	63.1
	Unknown199			2	1	1	38.4	14.8	0.55	316.2	50.9
	Unknown205			1	1	2	14.7	9.8	0.61	34.5	7.3
	Unknown223			1	1	1	43.1	26.8	0.51	689.7	102.5
	Unknown78			1	1	1	55.7	23.2	0.34	606.0	91.4
	Unknown130			1	2	1	10.8	6.1	0.54	10.6	2.6
	Unknown153			1	1	1	13.3	5.2	0.60	15.0	3.5
	Unknown154			1	1	3	24.3	14.0	0.60	131.0	23.5
	Unknown165			1	1	1	47.8	5.1	0.56	169.5	29.7
	Unknown182			2	2	6	10.9	6.1	0.55	11.0	2.6
	Unknown62			1	1	1	71.8	25.6	0.51	117.5	21.5
	Unknown83			1	1						
	Unkown181			1	1	2	115.1	28.3	0.48	4247.2	510.8
Asteraceae	*Vernonia amygdalina*	Native	Pioneer	14	14	5	14.6	6.2	0.60	21.7	4.8
Apocynaceae	*Voacanga africana*	Native	Pioneer	7	7	10	15.6	5.4	0.70	32.4	6.6
Combretaceae	*Anogeissus leiocarpus*			1	1	1	33.2	14.8	0.69	288.4	47.4
Arecaceae	*Caryota urens*			1	1	1	0.0	24.9	0.60	80.1	15.3
Arecaceae	*Oreodoza regia*			1	1	1	23.7	7.6	0.00	27.8	6.0
Clusiaceae	*Garcinia spp*			4	4	4	81.9	28.9	0.73	3363.2	415.5
Malvaceae	*Cola acuminate*			2	2	2	49.1	12.9	0.58	453.3	70.7
Myrtaceae	*Eucalyptus barteri*			2	2						
Fabaceae	*Cassia spp*			2	2	1	26.9	12.9	0.63	151.9	26.9
Sapindaceae	*Lecaniodiscus cupanoides*			1	1	1	38.7	13.6	0.64	331.9	53.7
Malvaceae	*Mansonia spp*			1	1	1	80.8	20.8	0.59	1955.6	257.4
Leguminosae	*Millettia spp*			2	2	3	34.4	7.6	0.74	624.0	88.4

Family	Species	Origin	Guild Type	Abundance in Kumasi	Abundance in Kumasi+Owabi	#Stems (trees)	dbh cm	Ht m	WD	AGC (kg)	BGC (kg)
	Unk_Acanthus_spp (vagari) possible A. vignei			2	2	5	45.4	19.9	0.55	564.9	85.1
Moraceae	*Ficus spp*	Native	NPLD	64	64	104	34.2	11.4	0.40	267.2	39.8
Rhamnaceae	*Maesopsis eminii*	Native	Pioneer	1	3						
Annonaceae	*Polyalthia oliveri*	Exotic	NPLD	44	52	43	16.1	8.0	0.54	38.5	7.6
Moraceae	*Ficus exasperate*	Native	Pioneer	16	28	8	24.2	9.6	0.44	95.8	16.9
Euphorbiaceae	*Euphorbia latifolia*	Exotic	Pioneer	3	3	1	33.9	7.9	0.54	126.8	22.9
Arecaceae	*Roystonia regia*	Exotic	NPLD	9	9						

Table A1.2 List of species indicating family, guild, and abundance in the Kumasi metropolitan area.

Family	Species	Origin	Guild	Abundance in Kumasi	Abundance Kumasi+Owabi
Sapotaceae	*Anningeria altissima*		NPLD		2
Leguminosae	*Anthonotha macrophylla*		ST		9
Sapindaceae	*Blighia welwitschii*		NPLD		1
Euphorbiaceae	*Bridelia atroviridis*		pioneer		1
Leguminosae	*Bussea occidentalis*		NPLD		3
Leguminosae	*Calpocalyx brevibracteatus*		ST		3
Polygalaceae	*Carpolobia lutea*		ST		1
Ulmaceae	*Celtis zenkeri*		NPLD		2
Araceae	*Cercestis afzelii*		ST		6
Sapotaceae	*Chrysophyllum pruniforme*		ST		1
Malvaceae	*Cola caricifolia*		pioneer		11
Leguminosae	*Daniella thurifera*	Native	Pioneer		2
Euphorbiaceae	*Discoglypremna caloneura*		NPLD		3
Malvaceae	*Dombeya buettneri*				2
Dracaenaceae	*Dracaena mannii*				1
Leguminosae	*Griffonia simplicifolia*		NPLD		45
Simaroubaceae	*Hannoa klaineana*		pioneer		2
Rubiaceae	*Heinsia crinita*		ST		2
Ulmaceae	*Holeptera grandis*		pioneer		1
	Hypoeetas velicillars	Uncertain			1
Bignoniaceae	*Kigelia africana*		NPLD		10
Sapindaceae	*Lecaniodiscus cupanioides*		ST		4
Leguminosae	*Lonchocarpus sericus*		NPLD		5
Euphorbiaceae	*Mallotus oppositifolius*		ST		7
Marantaceae	*Marantochloa congensis*		pioneer		5
Marantaceae	*Marantochloa leucantha*		pioneer		2
Euphorbiaceae	*Mareya micrantha*		ST		2
	Massularia acuminate		NPLD		2
Pandaceae	*Microdesmis puberula*		ST		7
Cecropiaceae	*Musanga cecropiodes*		pioneer		3
Lecythidaceae	*Napoleonaea vogelii*		ST		2
Rubiaceae	*Nauclea diderrichii*		pioneer		2
Malvaceae	*Nesodordonia papaverifera*		ST		4
Menispermaceae	*Penianthus spp*		ST		8
Lecythidaceae	*Petersianthus macrocarpum*		pioneer		2
Piperaceae	*Piper guineense*		pioneer		5
Sapotaceae	*Pouteria aningeria*				1
Anacardiaceae	*Pseudospondias microcarpa*				20
Malvaceae	*Pterygota macrocarpa*		NPLD		7
Arecaceae	*Raphia hookeri*		Swamp		7
Euphorbiaceae	*Ricinodendron heudelotii*		pioneer		2
Violaceae	*Rinorea spp*		ST		7
Menispermaceae	*Sphenocentrum jollyanum*		ST		2
	Tetrochiduim didynonstemon		pioneer		1
Meliaceae	*Trichilia monadelpha*		NPLD		48
Meliaceae	*Trichilia prieureana*		NPLD		4
	Trilepisium madasgascariense		NPLD		10
Verbenaceae	*Vitex grandifolia*		ST		1
Leguminosae	*Xylia evansiii*		NPLD		2
	Total			3757	4743

Appendix 2. Summary of ANOVA results for Carbon storage in Kumasi

A. Results for fix effect analysis: Vegetation Carbon

Command SAS:

```
Proc surveyreg data=tree_surv1;
strata urbanness;
class landuse urbanness;
model AGC = landuse urbanness landuse*urbanness / vadjust=none;
lsmeans landuse*urbanness / diff;
weight weight;
run;
```

Output:

Table A2.1 Test of effects model for the different dependent variables used in biomass analysis. P-values in bold indicate significant differences at alpha = 0.05.

Effect	DF	P-Values						
		AGC	BGC	BA	AGCT	BGCT	# of Trees	DBH(cm)
Model	14	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Intercept	1	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Land use	7	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Urbanness	1	**0.0190**	**0.0385**	0.2350	**0.0393**	**0.0487**	0.8460	**0.0144**
Urbanness*Land use	6	**0.0088**	**0.0097**	0.1178	**0.0020**	**0.0015**	0.1197	**0.0002**
Landuse*Ownership	9	**0.0004**						
Urban*Ownership	2	0.6540						
Urban*L_use*Owner	7	0.1105						

AGC – aboveground carbon (t/ha), BGC – belowground carbon (t/ha), BA – Basal Area (cm3/ha), AGC/Tree – Aboveground carbon (Kg/tree) BGC/Tree – belowground carbon (Kg/tree), No. of Trees per ha, DBH – diameter at breast (@1.33m above ground) height.

Table A2.2 – Test of effects models for tree cover and crop carbon in Kumasi metropolis. P-values in bold are significantly different at alpha = 0.05.

Effect	DF	% Tree Cover	Crop Carbon (Kg/ha)	Land Area
Model	14	<**.0001**	<.0001	
Intercept	1	<**.0001**	<.0001	
Land use	7	<**.0001**	<.0001	
Urbanness	1	**0.0288**	0.0077	
Urbanness*Land use	6	**0.0097**	0.0025	

B: Soil C and N Analysis

SAS command:

```
Proc surveyreg data=soil;
strata urbanness landuse/list;
class landuse urbanness Depth;
model pH = Depth landuse urbanness Depth*landuse Depth*Urbanness
Landuse*urbanness Depth*landuse*urbanness / vadjust=none;
*lsmeans Depth / diff plots=(diff meanplot(cl));;
weight weight; run;
```

Table A2.3 Summary of test of effects model for soil chemical (pH, C concentration, N Concentration, and Organic Matter) and Bulk density. P-values in bold indicate significance level.

Effect	DF	P-Values					
		pH	Bulk Density (g/cm3)	Organic C(%)	Total N (%)	SOC (t/ha)	STN (t/ha)
Model	41	**<.0001**	**<.0001**	**<.0001**	**<.0001**	<.0001	<.0001
Intercept	1	**<.0001**	**<.0001**	**<.0001**	**<.0001**	<.0001	<.0001
Depth	2	0.4069	**<.0001**	**<.0001**	**<.0001**	**0.0100**	<.0001
Land use	7	**<.0001**	**<.0001**	**<.0001**	**<.0001**	<.0001	<.0001
Urbanness	1	**<.0001**	**0.0082**	**0.0135**	**<.0001**	**0.0379**	**0.0032**
Land use*Depth	14	0.9033	0.2256	**<.0001**	0.3235	**0.0002**	**0.0030**
Urbanness*Depth	2	0.8933	0.2025	0.6846	0.9501	0.6093	0.4507
Urbanness*Landuse	7	**<.0001**	**<.0001**	**<.0001**	**<.0001**	<.0001	<.0001
Landuse*urban-ness*Depth	14	0.9591	**<.0001**	0.1697	**<.0001**	0.4104	**0.0424**

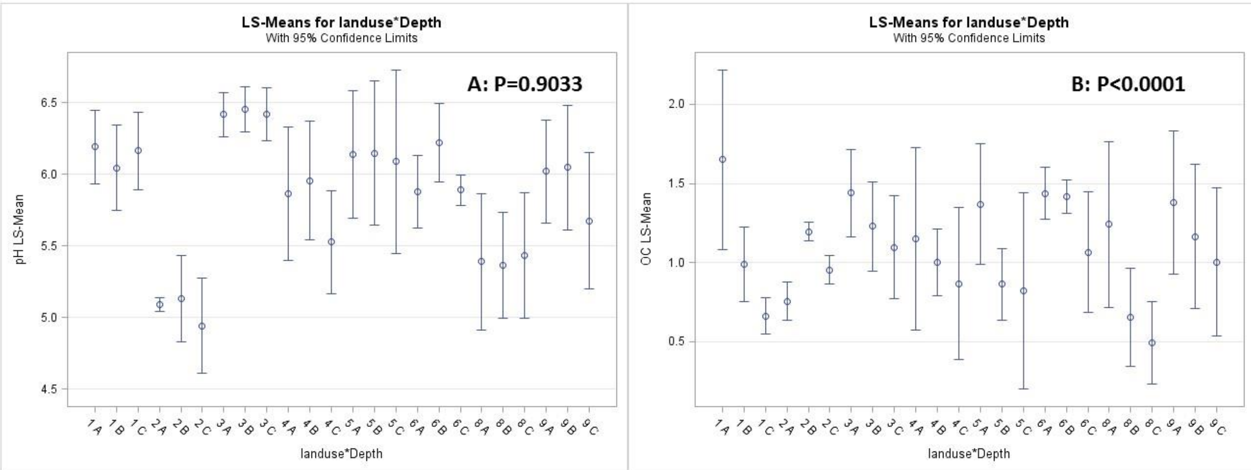

Figure A2.1 Soil pH (A) and soil organic carbon concentration in (gC/100g Soil) (B) changes with depth in different green space types in the Kumasi Metropolis. Green spaces labeled 1 = Plantation, 2= remnant natural forest, 3 = home garden, 4 = trees on compounds, 5 = farmlands, 6 = cemeteries, 8 = Public parks, and 9 = Grasslands. Depths A = 0 – 15 cm, B = 15 – 30 cm and C = 30 – 60 cm.

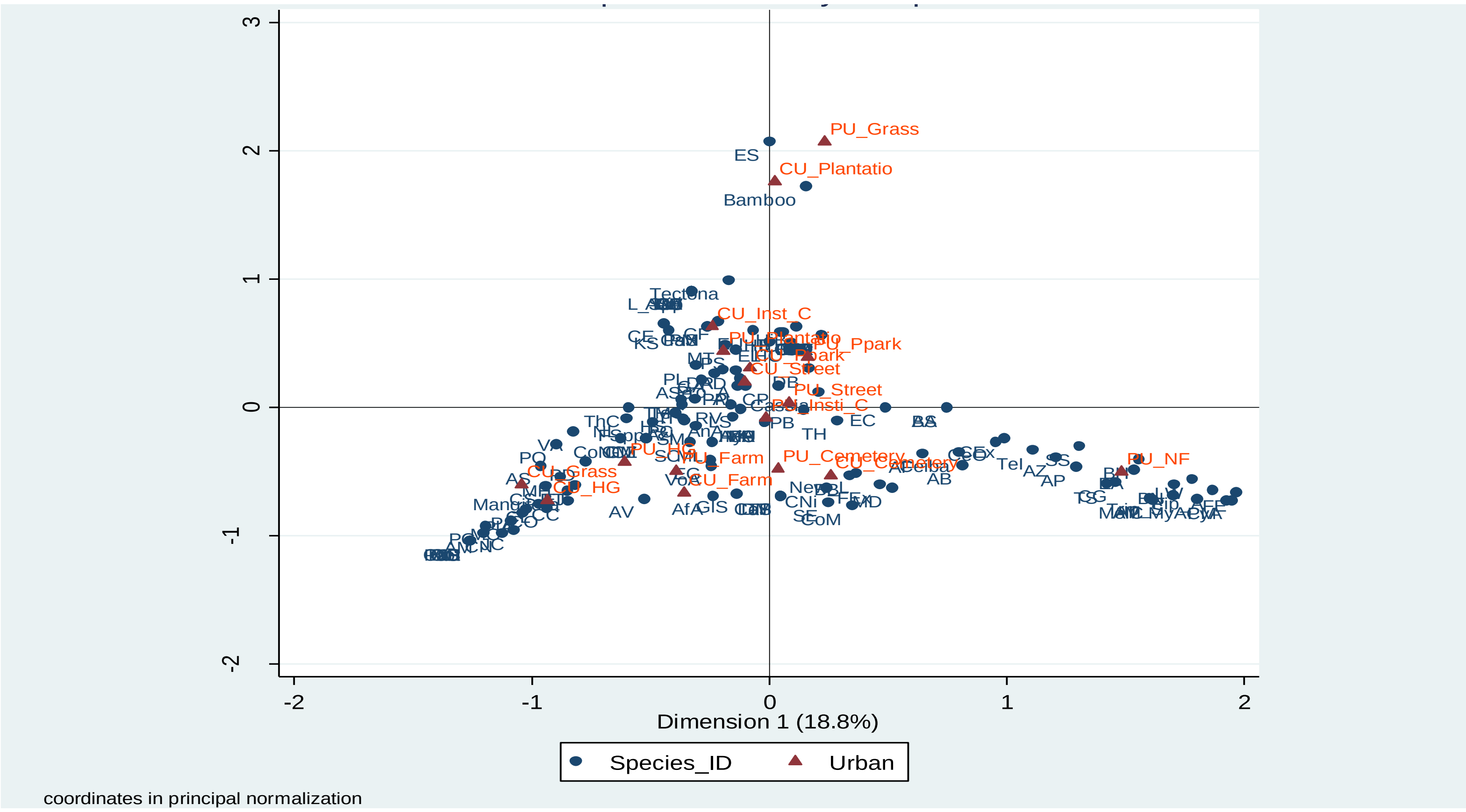

Figure A2.2 Correspondence analysis biplot of species associated with different Green spaces in different urban zones in Kumasi. Dimension 1 represents the combination of green space and urban zone whereas Dimension 2 represents plant species. Chi-square = 11169.8, Degrees of freedom = 2624. PU – Peri-urban, CU – Core Urban; Range = Rangeland, Plant = Plantation, Farm = Farmland, Cem = Cemetery, NF = Natural Forest, ST = Street, ICTre = Institutional Compound trees, HG = Home garden, Ppark = Public Park. List of species names and IDs see Figure 5.3.

Appendix 3: Description of Green space types in Kumasi

1. **Plantation** - Small slightly extensive patches of tree cover exist on mostly institutional (schools, hospital etc) land (Figure A4.1). They may be pure (single species) or mixed (multiple species) stands of either even or uneven ages. They range from fruit orchards e.g. citrus plantations, cocoa farm, to closed canopy woodlots such as *Tectona grandis*, *Gmelina arborea*, *Cassia siamea* stands. Patches vary in size but for the purposes of this work, a plantation should be at least 1 acre (436 m^2) large, have trees that are at least 5 m tall and consist of canopy cover of at least 80 %. Fruit orchards are mostly managed but majority of closed canopy woodlots in this category are rarely managed. Plantations are heavily littered with human excreta. Ownership can be either private or public.

2. **Natural Forest** - A natural forest in the urban matrix is defined here as a closed canopy woodland dominated by native tree species of primary or secondary forests. Relics of "true" natural landscape components, mostly protected areas towards the outskirts of the metropolis exist, e.g. Owabi wildlife sanctuary. Saplings and seedlings of shade tolerant tree species make up the bulk of the undergrowth with light demanders in gaps with adequate light intensities. Climbers and lianas are a major component of this green space type. They are mostly public property (owned), may be protected but not necessarily managed. Although rare, similar patches maay exist on private property.

Figure A3. 1 Pocket plantations in the Kumasi Metropolis: Woodlot at Menhyia Palace (A) and at Sawaba / Airport Area, Asawasi (B).

3. **Home gardens** - Vegetation found within homesteads or in residential neighborhoods (Figure A4.2). They are of 3 or 4 kinds: trees only (fruit trees), tree-crops mixed, grass lawns, and purely crops.

4. **Institutional compound** – A common feature of institutional (i.e. schools, hospitals, public administrative offices) lands are beautiful lawns with large shady trees (Figure A4.3). They may be scattered within compounds or planted around houses as fence trees.

5. **Farmlands** - Along water bodies in the city, it is common to find moderately large expanses of land cultivated with plantain, sugar cane, vegetables, and other crops. Their relative remoteness from houses and size are the main features separating farmlands from home gardens (Fig A4.4).

Figure A3. 2 Home garden at Akorem, Asawasi (A) and Edwenase, Kwadaso (B).

Figure A3.3 Institutional compound trees A: Roman Catholic Basic School, Asawasi and B: St. Joseph Basic School, Ashtown, Menhyia.

Figure A3.4 Urban agricultural fields A: Ayoyo garden at Nima/Airport, Asawasi, B: Corn farm at Opoku Ware School, Nhyieaso.

6. **Cemeteries /Sacred grooves** - The resting place of our forbearers and someday ourselves is home to several tree species of native and exotic origin (Figure A4.5). Most species are selectively preserved and strategically scattered within the cemetery yard. Several cemeteries are cultivated with crops e.g. plantain, cassava, corn in a seemingly agroforestry character.

Figure A3.5 Vegetation on cemeteries A: Tafo main and B: Boadi, Oforikrom.

7. **Street trees** – Trees along streets are not a familiar feature of the Kumasi Metropolis. Exceptions include, the Okodea road (KNUST) (Figure A4.6), Major Cobbina Drive, Harper Rd, Bekwai roundabout – Golden Tulip, Suame roundabout – Abrepo Junction.

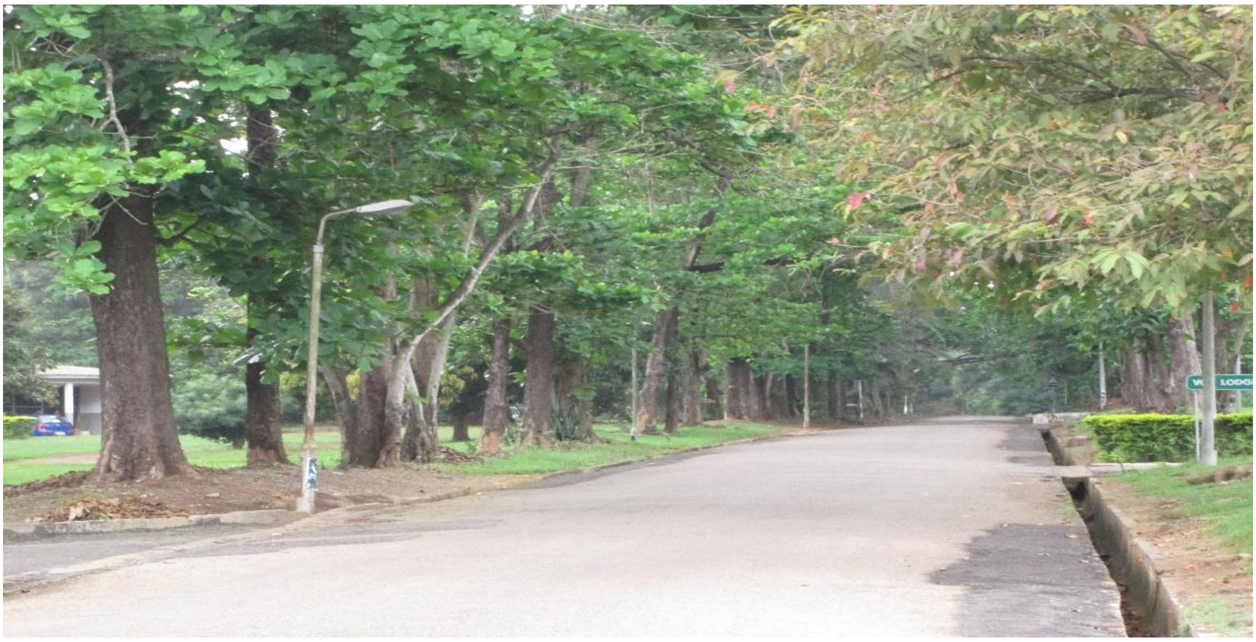

Figure A3. 6 Street trees along Okodea Road at KNUST campus, Kumasi.

8. **Public parks** – The once renowned "Garden city" of West Africa is fortified by six public spaces, two of which are the only functional and well maintained spaces remaining: the KNUST botanical gardens and the Zoo at Bantama. The golf course is actively utilized in this category.

9. **Grass/Range lands** - Adjacent farmlands especially in wetland areas are stretches of uncultivated fields

Figure A3. 7 Grasslands in the heart of the Kumasi metropolis. A) near Pelelee stream, Aboabo, Asawasi; B) along Sesa river, Bumso, Oforikrom.

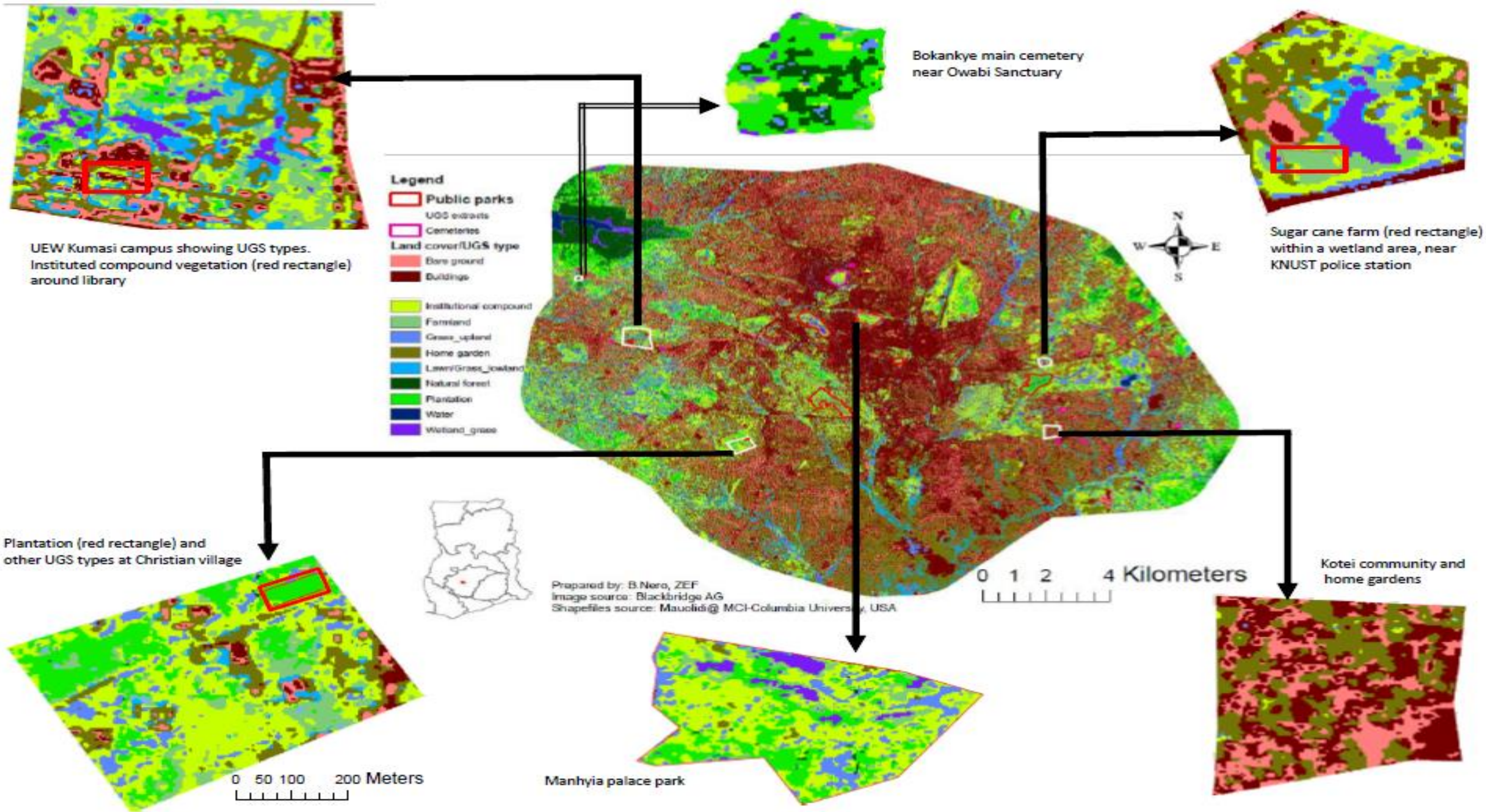

Figure A3.8 Green space map of Kumasi showing some extracts of green spaces.

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