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Deforestation and carbon stocks in Africa

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Contents

1. Introduction

1.1. Impacts of deforestation on carbon stocks

Tropical forests have been recognised to hold most of the world's biodiversity. The rapid decline of tropical forests has drawn concerns globally due to loss in carbon stocks, decline in species and the decline in the ability of these ecosystems to provide ecological and socio-economic services. The main driver of tropical forest carbon stock[1] loss is deforestation[2] (Rudel and Roper, 1996; Rudel et al. 2009). Deforestation is the main mechanism that determines net carbon flux from land use in the tropics; it brings about habitat loss and a decline in the ecosystem processes and services including the benefits derived by human beings and biomass decline within a given habitat. Deforestation is a phenomenon with severe consequences such as a reduction in CO_2 uptake by plants (Laurance 1999; Houghton 2005; Forster et al. 2007; FAO 2009; Achard et al. 2010;). Deforestation is important in the carbon cycle regarding emissions which the United Nations Framework Convention on Climate Change (UNFCCC) has recognised and in order to reduce emissions from deforestation and degradation (REDD) in developing countries, there has to be more accurate estimates and comprehensive studies on carbon stocks (Gibbs et al 2007). Achard et al. (2010) observed that tropical deforestation contributes to the emission of CO_2, non-CO_2 gases and a large loss in biomass per unit area relative to other factors that cause deforestation such as logging or grazing which reduce the amount of biomass lost. Land use change from deforestation and peat land degradation in the tropics during the period 1997 – 2006 resulted in the global net carbon emission of 1.5 x10^9 tons C yr^{-1} of which 1.22 x 10^9tons C yr^{-1} attributed solely to deforestation.

According to Gibbs et al. (2007) and Alexandrov (2007), forests serve as the largest terrestrial reservoirs of carbon and mitigate climate change. However, the removal or degradation of forest release the carbon stored in plants to the atmosphere as CO_2. Several studies including the studies by Noordwijk et al. (2002), and Olofsson and Hickler (2007), found that tropical forest ecosystems hold a large proportion of terrestrial carbon and major alterations in forest results in global carbon cycle modification and a change in carbon storage within an ecosystem. Degradation of forests thereby makes land use change the second most important source of atmospheric carbon asides fossil fuel use (Noordwijk et al. 2002).

Allen and Barnes (1985) noted that the rate of deforestation in developing countries has brought nations to the verge of being transformed to deserts and barren mountain watersheds. Moist tropical forests and their associated carbon stock are endangered due to increasing de-

[1]Above ground carbon stocks (also referred to as biomass in this study) according to Food and Agriculture Organization (FAO) of the United Nations, Forest Resource Assessment (FRA, 2005) is defined as "the quantity of carbon in a 'pool' i.e. a reservoirs system which has the capacity to store and release carbon which is found in living biomass above the soil including the stem, stump, branches, barks, seeds and foliage.

[2]Deforestation, according to Achard et al. (2010) and as adopted by the United Nations Framework Convention on Climate Change at COP-7 is the direct human-induced conversion of forested areas to non-forested lands.

forestation rates and climate change which have adversely affected biodiversity, soil, water resources, ecosystem processes and services, and the ability of ecosystems to resist disturbances subsequently affecting regional and global climate patterns (Cramer et al. 2005; Geoghegan et al. 2010).

In the tropics, it has been noted that land cover conversion is mainly for resource utilization. Ecosystems functions and services (e.g. carbon storage, biodiversity maintenance, nutrient cycling, erosion control, provision of food and pollination) are not considered during land conversion (Laurance, 1999; Malhi et al. 2008; Geoghegan et al. 2010). Vance and Iovanna, (2006) and FAO (2009), observed that 16% of the global forest is found in Africa, and over one-third of the earth's population depends directly on tropical resources economic and environmental goods and services. Africa holds 14% of the world's population, with forests occupying 21.4% of the land mass and the Congo basin being the second largest contiguous block of tropical forest. The population increased by 471million people from 1980 to 2006; the projected population by 2020 is 1.2 billion. This increase in population would increase the pressure on natural resources in Africa. In some instances according to Houghton (2005), there have been observed changes in biomass and no noticeable changes in area covered by forests; the observed change in biomass could be attributed to selective wood harvest, forest fragmentation, shifting cultivation, ground fires, browsing and grazing, recovering secondary forests that are not captured by satellite.

Apart from resource utilization, change in land use has been attributed to change in the circulation of atmospheric moisture brought about by reduction in rainfall (Laurance, 1999; Malhi et al. 2008; Geoghegan et al. 2010). Studies by Laurance, (1999), Bala et al. (2006) and FAO (2009) have shown that a decline in evapotranspiration rates, decrease in regional precipitation, increased sensible heat fluxes, surface temperature, increased regional albedo, which could potentially alter precipitation patterns; soil erosion, habitat degradation and increased frequency and severity of floods can be attributed to deforestation in the tropics.

Africa, from 2000 to 2005 has lost 4million hectares of forest annually, which is one-third of global deforestation rates (FAO 2005). Allen and Barnes (1985) noted the effect of deforestation can be felt in rural communities that rely on the functioning of ecosystems to produce goods and services that would improve the quality of their livelihood; large-scale loss of forest area can have global repercussions. Benhin, (2006) and Malanson et al. (2006) observed that forest remnants undergoes changes during and after deforestation, because it becomes, to some extent, an island, being smaller and more isolated, making the forest unable to support all the species that it held as part of a larger habitat area. Mertens and Lambin, (1997) proposed that the utilization of forest resources in a sustainable manner would not impede the forest's ability to perform all its functions in the long-term but would maintain the forests' ability to meet the needs of the present and future generations. Tropical deforestation is a threat to socio-economic development and ecological sustainability; effective management of resources could stem the effect of deforestation on the continent's carbon stock and the global carbon cycle. Estimating carbon flux from deforestation requires that all estimates of land use changes must be accurate (Achard et al. 2010). Houghton (2005) noted that an adequate knowledge of the spatial distribution of biomass would aid our understanding of change assessment through time, carbon sources and sinks due to conversion, afforestation and reforestation efforts. The role of carbon stocks cannot be over emphasised in the global carbon cycle, climate change and biodiversity conservation. This study intends to simulate the spatial and temporal trend in carbon stocks in Africa, the amount of carbon lost to deforestation and the potential role of African as a sink or source of carbon. The possible effects of deforestation on ecosystem services in Africa and the overall effect land use change has on the global carbon cycle are also examined in this study.

1.2. About this study

Estimating and mapping biomass enables to quantify spatial and temporal distribution of biomass in Africa. This study will present maps and graphs of biomass changes by analysing MODIS VCF percent tree and grass cover in conjunction with simulated biomass from LPJ-GUESS and FAO country-specific deforestation rates for year (1990 – 2000) for Africa. This study aims a) to assess the impact of deforestation on biomass and b) to simulate how much biomass is lost on a continental scale and country-specific basis in Africa. The following questions need to be answered: a) how much carbon stock does the continent hold during the study period 2001 – 2030? To estimate the quantity of biomass held in vegetation. b) What is the spatial distribution of Carbon stock across the continent? This would show where biomass is concentrated in Africa. c) What regions and countries have large quantity of carbon stock, and how much of this carbon is lost due to deforestation? This study had some assumptions such as: a) the change in forest cover for the year 1990 - 2000 remained constant for the study period (2001 – 2030), to observe the effect change in forest cover has on the above ground carbon stocks. This would help mitigate increase in forest cover change. b) The deforestation rate for each country was applied to the biomass found in each grid cell located within a given country.

This study focuses on the spatial and temporal relations among the 30 year's data displaying years 2002, 2015 and 2030. The data used for analysis is derived from same data sets comprising of FAO forest cover change for the period 1990 to 2000 which was extrapolated over 30 years, MODIS VCF 2000 dataset for percent tree and grass cover and LPJ-GUESS biomass for herbs (represents grasses in the model) and trees.

The structure of this report is as follows: Section 1 gives an introduction to carbon stocks and deforestation impacts on tropical ecosystems, the causes, past trends and future predictions on the impact of deforestation. Section 2 describes all the data used in this study. Section 3 gives a concise description of the data analysing methods, including the GIS tools used. In Section 4, the analysed results for total biomass, tree biomass and grass biomass are presented on (continent, region and country) basis respectively. Sections 5 and 6 are the discussion and conclusion respectively.

1.3. Drivers of deforestation (biomass loss) in the tropics

Understanding the spatial and temporal effect of land cover changes on ecosystems is important; the effect the drivers and mechanisms responsible for these changes in land cover have on conservation of biodiversity is crucial (Lambin and Ehrlich, 1997; Puyravaud 2003). According to Cramer et al. (2005) and FAO (2009) increase in deforestation trends could lead to accelerated biodiversity loss, in relatively well-off countries that have weak institutional capacities, impeding the supply of forest-derived ecosystem services; involving the relevant stakeholders in forest resource management could abate this decline. According to Ning Zeng (1998), the impact of forest loss varies and this has led to arguments regarding the severity of forest loss in relation to the area lost to deforestation due to the frequency of occurrence which is averagely less than 1% of forest per area. Allen and Barnes (1985) and Ning Zeng (1998), observed that although scientist agree that deforestation is real but opinions vary regarding the magnitude, causes and consequences of deforestation such as the definition of forest area, changes over time which have made comparing estimates of deforestation rate difficult and vary across regions.

Cramer et al. (2005) and FAO (2009) mentioned that the most cited causes of deforestation in the tropics are forest conversion to pasture for cattle grazing, agriculture, crop land expansion and intensive fuel wood harvesting and exportation, over grazing and rapidly increasing population which has been observed to be correlated with the state of the world's forests, and infrastructural development, construction of roads, dams and urban settlements. These actions have various effects socially, economically and ecologically, which could be destructive or constructive depending on the ecological conditions and the economic development of the region.

Man has been at the centre of deforestation over the years but, the rate at which forested areas are converted and the subsequent effects vary. Evidence from Allen and Barnes (1985), Zhang et al. (2001), Houghton (2005), Olsson and Hickler (2007) and several related studies, indicate that the accelerated expansion of forests to agriculture, arising mainly from rapidly increasing population pressure, is the main driver of deforestation and source of carbon emission from terrestrial ecosystems.

1.3.1. Past Drivers (Pre-industrial)

In the past, deforestation was attributed to shifting cultivation and fallow system with most Africans being engaged with gathering and hunting after the 1950. There has been an observed acceleration in the rate at which carbon stock was lost due to agricultural expansion and population growth. Prior to 1961, land in sub-Saharan Africa was used for hunting, gathering, herding and shifting cultivation. Late in the 19th century during the colonial era, lands cultivated were left fallow for long periods as cultivators moved to new lands and cleared them for cultivation. There was an assumed decline in African population during the colonial period due to slave trade, despite this, in 1930 changes in land cover and land use in Africa accelerated with development of railroads and other transport routes, increased population and export trade of crops the combination of all these led to accelerated changes in Africa biomass(Rudel and Roper, 1996; Houghton and Hacker 2006; Rudel et al. 2009). The combination of demographic pressure and need for improved infrastructural development have continued to accelerate deforestation (National Geographic Society, 1996; Houghton and Hacker, 2006). Olofsson and Hickler, (2007), mentioned in their study that the drivers of forest conversion which commenced at about 11,600BP was agriculture and pasture development with the introduction of agriculture and pasture development, in 1750, the estimated global land surface conversion was 6 – 7% which accelerated in 1850 to 14% and 34% by 1990. Anthropogenic activities that have impacted land cover change include pasture, urbanization, plantation and cropping; this affects the biogeochemical cycles altering atmospheric compositions and modifying ecosystems. Accelerated tropical rainforest depletion has been observed since the 1950s, which accounts for the present land-use related emission.

In the early 1970s as mentioned by Melillo et al. (1996), awareness on deforestation in developing countries emerged due to studies carried out which, indicated the severity of environmental damage and wood shortages to the livelihood of the people; the effect of deforestation has been reiterated and systematized by graphically demonstrating erosion in mountainous regions and desertification in semi-arid tropics as well as emphasizing species and ecosystem loss. The impact of deforestation varies based on the amount of forest area lost and this argument has evolved to the severity of deforestation based on the extent of forest area lost (Rudel et al. 2009). Tropical deforestation in the 1980s was a major driver of CO_2 flux to the atmosphere. The accelerated rates of deforestation was observed by Forster et al. (2007), and Olofsson and Hickler (2007) in their study over the tropics, Latin America, Africa and South and Southeast Asia experienced slow cropland expansion until the 20th century, but have had exponential increases in the last 50 years. By 1990, croplands and pasture covered 45.7 to 51.3 million km^2 (35% to 39% of global land), and forest cover had decreased by roughly 11 million km^2, subsequently, until the mid-20th century most deforestation occurred in the temperate regions (FAO 2005). In Western Europe and North America, land abandonment has been leading to reforestation while deforestation is now progressing rapidly in the tropics. In the 1990s compared to the 1980s, net removal of tropical forest cover had reduced in the Americas but increased in Africa and Asia (Olofsson and Hickler 2007). Globally, Scientists estimate that the destruction of one-fifth of the global tropical rainforest took place between 1960 and 1990. In 1900, about 90% of West Africa's coastal rainforest disappeared, with South Asia losing 88% since the 1950 and two-third of Central America's lowland tropical forest has been converted to pasture; 40% of all the rainforest in the region have been cleared in the last 40 years (National Geographic Society 1996; Cal Poly Pomona University- Bio Trek facility and John Revington 1992).

Melillo et al. (1996) and Canadell et al. (2009) found that deforestation for Agriculture accounted for most of the emissions (41% for permanent croplands; 48% for shifting cultivation). Industrial wood harvest accounted for 11% of the total net flux from 1990 to 2005. Countries in Africa show small differences in the historical pattern and emission magnitude. Only in North Africa, where the establishment of plantations has recently, exceeded deforestation and serves as a carbon sink of $3x10^6$ tons C y^{-1}, which is relatively small in comparison to the sources from the other regions that experience $4x10^7 – 7.2x10^7$ tons C $yr\text{-}^1$. The size of the forest and the definition of deforestation and the direct and indirect drivers of deforestation could be attributed to what brings about variations regarding extent of tropical deforestation (Gibbs et al. 2007). According to IPCC report as mentioned in Nsabimana Donat (2009), recent increases in anthropogenic activities such as fossil fuel combustion, cement production, land use change and burning of biomass emits $8.0 \text{ x } 10^9$ tons C $yr\text{-}^1$, altering the global carbon cycle which contributes to climate change.

1.3.2. Present Drivers

1.3.2.1. Climate

Presently, the drivers of deforestation do not vary from the past but are intensified due to climate variability and extreme climate events such as the prolonged drought in the Sahel region (Allen and Barnes, 1985). Deforestation affects the global climate due to human-induced land use change in the conversion of forest, however; natural disasters such as fires and landslides due to climatic variations can cause forested area to disappear. According to Boko et al. (2007), there is a medium – low level of scientific understanding on changes in land cover, largely due to net deforestation. Deforestation has led to increased Surface albedo, global mean annual precipitation in the tropical forests, mean temperature and the mean insolation. Long periods of drought in some regions coupled with man-induced deforestation have led to desertification in these regions (Hassan and Hertzler, 1998, Malhi and Wright, 2005). Bettwy Mike (2005) suggested that an improved understanding of forested tropical regions is important in understating their influence on global climate because the tropics receive about two-thirds of global precipitation. The release of latent heat during rainfall, serves as a store and source of heat energy: making the tropics a primary source in global heat distribution. Ning Zeng (1998) noted that the relationship between climate and deforestation is not clear cut but the implication is that due to water stress and variations in precipitation on the continent, some regions may be drier than others and these drier regions are more liable to be deforested consequently modifying the climate. This indicates that the fate of tropical rainforests is not solely determined by climate but by human activities in the utilization and protection of the forests.

1.3.2.2. Agriculture

Ning Zeng (1998) and Benhin (2006) in their respective study found that about 90% of tropical forest conversion to agricultural fields for cultivation and pastures for grazing is attributed to rapidly increasing population and the high demand for food. It has been observed by Ning Zeng (1998), that countries lacking improved agricultural practices and productivity are prone to have more forested areas cleared. FAO (2009) stated that about 59% of deforested areas in Africa are converted to small-scale permanent agricultural fields, making agriculture the major driver of deforestation in the region. Benhin (2006) stated that deforestation in the short-term in developing countries is perceived as an equivalent to good and cheap fertilizer for increased agricultural production; although forest contributes, in the short term to increased agricultural production but depletion in the long-run generated a decline in agricultural production. The natural vegetation in the tropics rather than the soil is the most important store of nutrients. Several studies (e g Benhin, 2006) show that natural biomass is positively correlated with increased agricultural production, because burned natural biomass from forests aids agricultural production; slash and burn practices are beneficial in crop production and cattle pasture. Most tropical soils owe their productive qualities to the protective role of the forest, which is accelerating formation of topsoil, creating favourable soil structure, and nutrient storage, which is useful for crop production by reducing erosion, silting and stream flow regulation. When forest is cleared, the soil chemical and physical properties are altered leading to nutrient loss, accelerated soil erosion and declining productivity. The expected higher benefits from agriculture as compared with the marginal benefits from forest are the primary factor that influences increased conversion. Benhin (2006) noted that before 1960, 73% of forested land was converted to pasture and arable farmlands with land degradation accounting for a 14% loss of forest; the introduction of cash crops such as coffee and cocoa and rising population and pressure on natural resources were responsible for deforestation in Africa. The Democratic Republic of Congo which holds about 47% of forest in Africa has recorded the highest loss of forest cover over a ten year period from 1990 to 2000. About 180,000 hectares (0.2%) of forest is lost annually to forest encroachment by smallholder farmers, other contributing factors are fuel wood harvesting, fires and government policies. Major causes of deforestation were shifting cultivation, planned agriculture conversion, logging and normal fire loss. Population pressures and economic policies worsened the problem of deforestation (FAO, 2005). According to Allen and Barnes (1985), the rate of deforestation for agricultural purposes tends to be higher in countries where the agricultural productivity declines after forest clearance. This increase in the area of forest cleared occurs also in countries that practice shifting cultivation and those that are transiting to permanent cropping systems, resettlement schemes in some countries contributes to forest clearance. The accelerated demand exceeds the carrying capacity of the forest to provide wood, food and environmental protection for the people that depend on the forest for their survival.

1.3.2.3. Logging, Fuel wood, Burning and Grazing

Uncontrolled intensive, extensive and commercial timber extraction, which is not an outright clearing of the forest, depletes forests stocks. Most developing countries do not have policies that regulate timber extraction, which abruptly disrupts the character of the forest. Timber harvesting brings about construction of roads into forested areas, subsequently giving access to farmers in search of new land for agriculture to clear and farm. Agriculture encroachment and logging are the driving factors of deforestation in some African countries. Other drivers are fire, mining and quarrying and plantation activities (Allen and Barnes, 1985; Ning Zeng 1998; Benhin 2006). According to Ning Zeng (1998), increased oil prices has led to an increase in the demand for fuel wood for domestic cooking and heating by the local population who harvest fuel wood in woodland, and forests. Most households in low-income countries as noted by Allen and Barnes (1985) depend on fuel wood for energy, the urban and rural populations depend on fuel wood from forests: fuel wood and charcoal account for 95% of the total energy used in small industries such as brewing, baking and brick making industries. In their study, Hassan and Hertzler, (1998) speculated that over 50% of annually removed Woodstock is used as fuel in central and eastern African countries. Annual forest burning, grazing, ploughing or clearing also contributes to deforestation because it leads to erosion or soil compaction, which reduces nutrients, productivity and the ability of the ecosystem to regenerate naturally (Allen and Barnes, 1985).

1.3.3. Future Predictions

FAO (2009) mentioned that there would be an increased occurrence of drought, floods and water scarcity which could weaken sustainable forest management efforts in the region. It has been observed that deforestation contributes to climate change including, climatic variations, fires and landslides, it also affects forest cover. Increased deforestation rates would bring about untold hardship to the people of Africa due to change in global climate and the global carbon cycle (FAO 2005). The interaction between deforestation and climate is intricately linked; release of CO_2 from forests brings about increased atmospheric CO_2 and climate change of which invariably affects the global carbon cycle. Tropical Africa climate differs from other tropical climates as mentioned by Nsabimana Donat (2009). Africa has lower precipitation and high water stress because Africa is situated at higher altitudes. There is an expected increase in warming on the continent according to Boko et al. (2007) of 0.5 ºC during the 20th century of which June-august will be the warmest months. The surface temperature is expected to increase between 2-6 ºC in the next 100 years, this buttress the need to forecast the impact of carbon storage and fluxes in Africa. There have been few attempts made to examine the interactions between tropical rainforests and climate trends. The focus has moved to understanding how climate change influences tropical rainforest ecology and function. Variability in climate trends at interannual, interdecadal and intercentinnial has been observed in the tropics. The intensity of dry season, which results in drought in the region, could affect forest structure and adaptation of the species within the biome. Climate models have shown a drying trend in African tropical rainforest, which is, attributed to the prolonged drought in the Sahel region during the second half of the twentieth century. This drying trend contrasts with prediction of increased precipitation caused by global warming (Malhi and Wright, 2005). According to the FAO (2009) State of the World's Forest report, in North Africa, the economic situation would reduce pressure on the natural resources especially the land and this could subsequently lead to forest re-growth in cleared forest areas but the increase of investments in large-scale agriculture may negatively reverse this trend. Due to the high population density and limitation in economic diversity in eastern and southern Africa there has been an increased pressure on the forest resources, which has led to land use conflicts in the region and may increase land use conversion. Benhin (2006) stated that accessibility to large expanse of forested areas in Central Africa may favour forest conversion for commercial and subsistence agriculture. The demand for fuel wood and agricultural products in the urban areas may increase. This implies a continued reduction in forest cover within the West African region. It is estimated that the African forest (Cameroon) would disappear in the next 150 years (Benhin, 2006). Projections from other studies indicate that if the current trend of severe forest clearance observed between 1958 and 2000 continue, then one-third of the world's forest area would be lost; most of the deforestation is expected to occur in developing countries where the projected annual loss is 3% - 6% in certain nations while others are expected to experience an accelerated deforestation rate implying that fuel wood supplied would diminish and not be able to meet the demands of the rapidly increasing population before year 2000 in most developing nations. This increasing demand for fuel wood would lead to conversion of more forest area to plantation to meet the fuel wood demand. There could be errors generated from the projections based on the time frame of the observed data obtained on the forest areas, the scale of the area and the practical and appropriate technology for forest inventory (Houghton 2005; FAO 2009).

1.4. Biomass modelling using Dynamic Global Vegetation Models (DGVM)

Dynamic global vegetation models (DGVMs) have been used to bridge the gap in understanding and quantifying the global pattern of terrestrial ecosystems as major drivers in the dynamics of the earth systems including the effects of atmospheric CO_2 concentrations and climate on global carbon storage in vegetation and soil (Sitch et al. 2003). Malanson et al. (2006) stated that the modelling of forests covers a wide range of problems and approaches. At the global scale there are more mechanistic models that are primarily concerned with forest growth and carbon balance, also there are more phenomenological models that attempt to capture multi- species dynamics, to the other simplified models that are calibrated to capture more abstract notions of dynamics; models are the standard for simulation of deforestation and/or its consequences. Modelling spatial and temporal changes in biomass aids planning, effective management of natural resources and climate change mitigation.

DGVMs are suitable for global to regional assessment of terrestrial biomes. The Lund Potsdam Jena-Dynamic Global Vegetation Model (LPJ-DGVM) is a coupled process-based biogeography – biogeochemistry model that incorporates terrestrial dynamic vegetation structure and composition. These processes of vegetation dynamics include growth, competition and demographic processes. LPJ-DGVM uses plant functional types (PFTs) to simulate biomass based on the bioclimatic niche under investigation (Cramer et al 2004; Hickler and Olofsson, 2007). Biomass estimation is crucial in understanding the carbon flux from terrestrial ecosystems to the atmosphere. The above global vegetation model strived to simulate biomass annually (Smith et al. 2001; Sitch et al. 2003). Modelling and analysing biomass using Lund Potsdam Jena- Generalised Ecosystem Simulator (LPJ-GUESS) according to Tang et al. (2010) enhances long-term spatial and temporal observation of changes in terrestrial carbon stock, dynamics of forest distribution and composition to study forest biomass and its associated changes. Several models such as Marine Biological Laboratory/Terrestrial Carbon Model (MBL/TCM) and LPJ-DVGM have been developed and used to estimate forest biomass and the flux of carbon from terrestrial ecosystems to the atmosphere at broad spatial scales (Melillo et al. 1996; Smith et al. 2001; Sitch et al. 2003). The defects of most DGVMs are that patterns and variability in biomass estimations are global; therefore it produces generalised estimates which are unreliable at the regional level (Tang et al. 2010). LPJ-GUESS is designed to produce temporal and spatial variability of forest structure and function by differentiating tree life history groups, class age/ size and competition for resources at the regional scale, making LPJ-GUESS an appropriate model that can be used to estimate biomass for Africa (Tang et al. 2010).

LPJ –GUESS is a landscape version of LPJ-DGVM with similar land-atmosphere coupled to vegetation processes represented at local to regional scales. This model is made up of certain modules formulations that are comparatively well-defined, subsets of ecosystem processes with distinct spatial and temporal scales. Processes such as photosynthesis, stomatal conductance and respiration are implemented on a daily time step, growth and allocation, population dynamics and disturbance are simulated on an annual time step. The model has been shown to reproduce global patterns of vegetation distribution (Smith et al. 2001; Tang et al. 2010).

The input variables of the model are atmospheric CO_2, a soil code to derive texture-related parameters governing the hydrology and thermal diffusivity of the soil and climate data (daily or monthly air temperature, precipitation and incoming radiation). LPJ is a DGVM of intermediate complexity, having generalised Plant functional types (PFTs), vegetation dynamic processes e.g. growth, plant demography and competition as well as natural fire disturbance (Smith et al. 2001; Malhi and Wright 2005; Tang et al. 2010).

1.5. Change detection of Carbon stock using satellite data

Estimating change in areas covered by biomass without using remotely sensed satellite data would prove challenging due to accessibility and size of the region (Hansen et al. 2003). A combination of ground measurements and satellite data are important in measuring and monitoring forest cover loss. Accurate estimation of land use change that lead to carbon flux in the tropics using ground measurements and satellite data would reduce uncertainties of observed estimates in all forests located in the tropics (Achard et al. 2010). Global forest cover maps serve diverse aims, including the ability to estimate parameters used in biogeochemical modelling processes, vegetation delineation for conservation and forestry purposes, these maps reveal land use patterns and potential vegetation conditions depicting human impact on natural ecosystems. Several attempts have been made to monitor present and future changes in forest ecosystems, global satellite data sets provides the best possibility of creating such maps (Hansen et al 2003). Observation of changes in biomass has been made from satellite imagery such as the moderate resolution imaging spectroradiometer (MODIS) on board the Terra and Aqua platforms. The Products such as the Vegetation Continuous Fields (VCF) product is used for monitoring changes and mapping global land and forest cover; which have spatial and thematic refinements due to the greater stability of the platforms and the sensor's spectral characteristics as compared with previous coarse resolution sensor the advanced very high resolution radiometer (AVHRR), (Hansen et al. 2003; Achard et al. 2010).

The rapid development in the use of remote sensing techniques in monitoring land use changes at spatial scales according to Lambin (1995) and Achard et al. (2010) enhances our understating of the drivers of change and enables the forecast of ecological and socio-economic implications of these observed changes; the maps obtained from satellite data aid the estimation of forest biomass through and can be used as complementary forest maps especially ecosystem stratification.

Remote sensing aids identification of deforestation hot spots such as the presence of fires, increase in forest fragmentation and the use of change detections techniques. The use of remote sensing may lead to land use change estimation to predict future forest changes (Lambin 1995).

Hansen et al. (2003) noted that remote sensing is advantageous because of its consistency and short time-intervals between observations of phenomenon on the surface of the earth; although cloud cover present problems which are resolved by approximate methods. It has been a challenge in the past to estimate deforestation in large and remote regions of the world until the advent of satellite remote sensing. The combination of satellite remote sensing with ground measurements is important in the analysing forest cover loss. Recently, remote sensing has been used in the mapping of global forest cover as shown by Hansen et al. (2003). Vegetation sensors on MODIS have produced global land cover datasets; these datasets are used for spatial and thematic refinements of previous global maps due to the spectral characteristics of the sensors and the stability of the platforms on which they are mounted. Nelson and Geoghegan (2002), observed that spatially referenced data on land use/cover are needed to estimate deforestation rates but for remote locations and in most developing countries, spatially explicit data collected on the ground are difficult to obtain and an alternative to field data is the availability of remotely sensed data.

2. Data

2.1. Study Area

Africa is located along longitudes 17.52°W through 51.38°E and from latitudes 37.34°N through 34.80° S. Africa has a wide range of heterogeneous vegetation found in different ecosystems; the tropical rain forest is found along the equator occupying most of Middle Africa, the coast of West Africa and Madagascar. Tropical moist deciduous forests are located to the north and south of the rain forests with Mozambique and Madagascar having patches, the tropical dry forest extends to the north and south of the tropical moist deciduous, Tropical shrub lands, Tropical mountain forests (sub-montane and montane forests).

The variations and distribution of these ecological zones depends on mainly on climatic variables such as temperature, rainfall; topography and soils. Vegetation distribution in the region depends on the intensity and type of human activities prevalent in a given area, the forests, woodlands and savannah ecosystems experience concentrated human activities. As shown in figure 1, the ratio of grass cover to tree cover varies in Africa. Tree cover is found more in Central African region, along the coasts of West Africa and Madagascar.

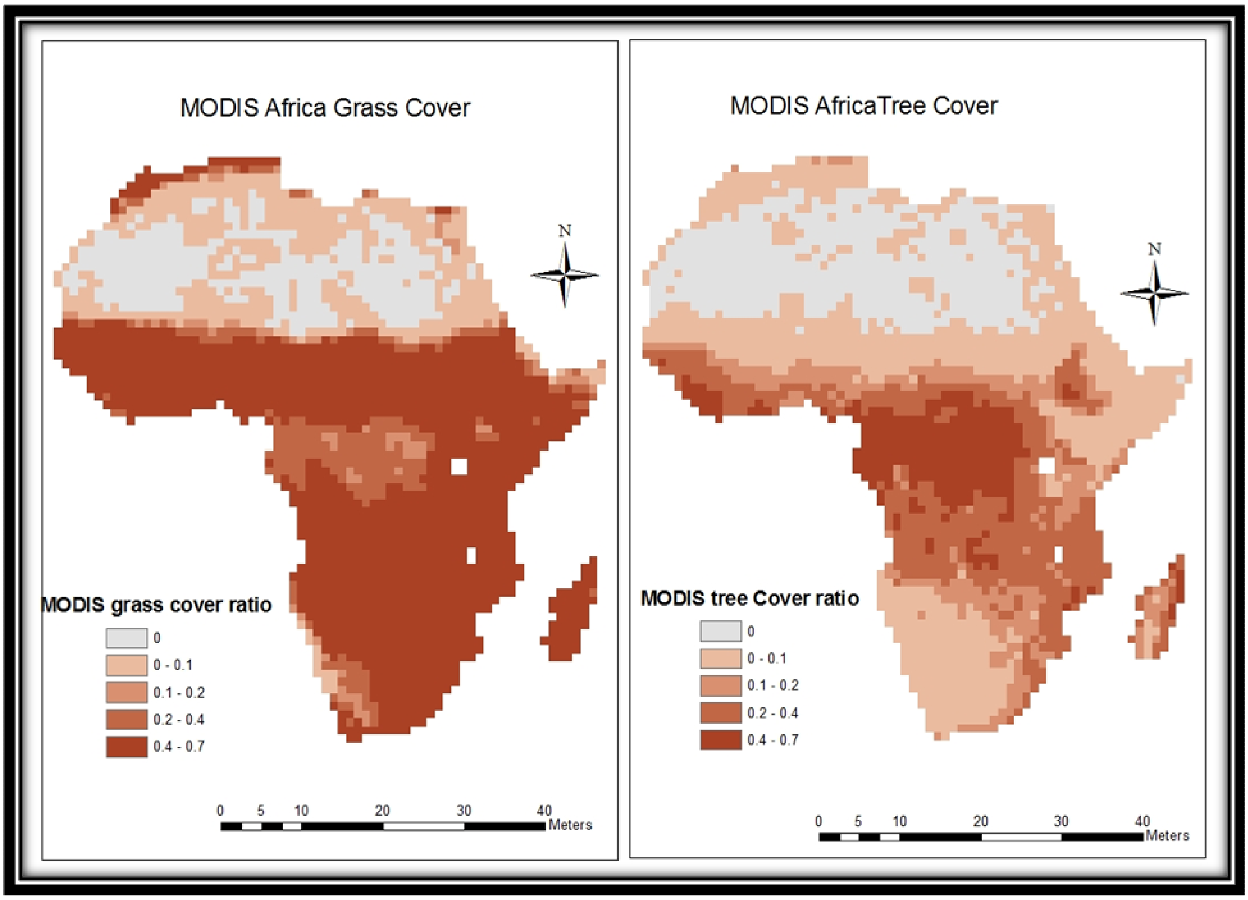


Figure 1: Showing the spatial distribution of Grass and Tree cover ratio for Africa from MODIS VCF 500m data.

This study concentrated on 49 African countries; East Africa (Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mozambique, Rwanda, Somalia, Uganda, United Rep. of Tanzania, Zambia and Zimbabwe), Middle Africa (Angola, Cameroon, Central African Republic, Chad, Congo, Democratic Republic he Congo, Equatorial Guinea and Gabon), North Africa (Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Sudan, Tunisia, Western Sahara), South Africa (Botswana, Lesotho, Namibia, South Africa, Swaziland) and West Africa (Benin, Burkina Faso, Cote d'Ivory, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Senegal, Sierra Leone and Togo) except the islands of Africa (Brown and Gaston 1995; FAO 2005; Houghton and Hacker 2006).

2.2. MODIS Vegetation Continuous Field (VCF) (500m)

This study used the collection 3 release of Moderate Resolution Imaging Spectroradiometer (MODIS) monthly composites of 500 meter Vegetation Continuous Field product (MOD44B). The NASA MODIS sensors on board Terra satellite provide better proportional estimates of woody and herbaceous vegetation as compared to other coarse resolution satellite such as the advanced Very High Resolution Radiometer (AVHRR) which has a resolution of 1km (Hansen et al. 2003). The MOD44B data was produced using monthly composites of 500m resolution MODIS data and the MOD09A1 surface reflectance. Eight-day composites were used as inputs to remove clouds and cloud shadow. All 7 MODIS 500m land surface reflectance bands were used: the red (620-670 nm) and near infrared (841-876 nm) bands had a resolution of 250 m and the 500m resolution bands are (blue (459-479 nm), green (545-565nm), and middle infrared (1230-1250nm, 1628-1652 nm, 2105-2155 nm) which was used to derive the metrics for computing percent tree cover. MODIS 500m percent tree cover is estimated using a supervised regression tree which is a non-linear, distribution free algorithm, suited for handling complex global spectral land cover signatures (Hansen et al. 2003; Hansen et al. 2008). The data generated from MOD44B data represents global percent tree cover as compared with AVHRR (1km). MODIS has bands designed primarily for land cover monitoring yielding an improved spatial and temporal response to enhance greater accuracy due to the robustness of spectral signatures. Noise and atmospheric scattering is limited in these bands of MODIS (Hansen et al. 2003).

The MODIS composited data were transformed into annual metrics of maximum annual NDVI to capture the phenologic cycle. The maps generated from this data could serve varied scientific applications as compared to previous coarse-scale maps. MODIS VCF is used to monitor tree cover, which is defined as the percentage of ground surface area covered by a vertical projection of live tree crowns, which could be any woody plant greater than or equal to 5meters in height. Tree cover strongly influences processes in carbon cycle simulation, bird habitat, and soil erosion. A global 500m spatial resolution, per cent tree cover product exhibits general realistic global patterns (Lambin and Strahler 1994; Lambin and Ehrlich, 1997; Hansen et al. 2003; White et al. 2005; Achard et al. 2010).

2.3. Food and Agriculture Organization (FAO) of the United Nations

According to FAO (2001), the data sets used to map and estimate forest area and forest area change is the sum of natural forest and forest plantations. Forest area change includes the expansion and reduction in forest size. The FAO has obtained data from national statistics and forest inventory on a country-by-country basis using the method shown in figure 2, the data contains detailed information on the forests of individual countries.

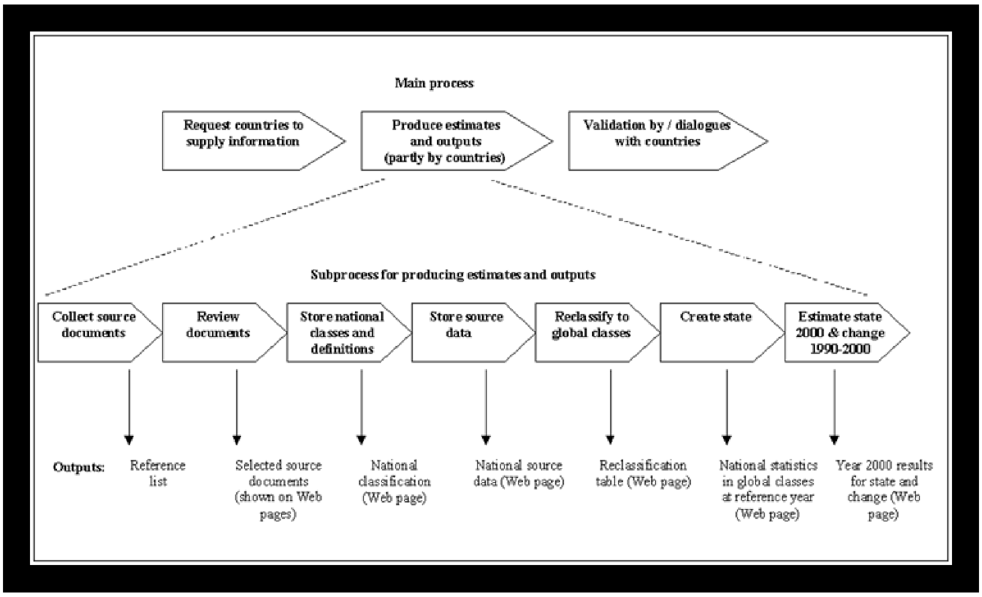


Figure 2. The processes undertaken in developing and estimating forest cover using country information. Source FAO 2001.

Forms requesting countries to give information about the status of forest area is dispatched to the respective countries. There are specific criteria specified by FAO for the estimating forest area change. The estimate produced by countries based on the feedback FAO obtains is validated through dialogue. The data is collected and reviewed on a global to regional scale based on population, gross domestic product (GDP) and areas occupied by vegetation (forests or plantation). Based on the flow chart shown in figure 2 above, the estimates of change in forest area are derived for the period under review.

Annual rates of deforestation, given in percentage, were obtained from the Food and Agriculture Organization (FAO) of the United Nations; State of the World Forest 2003 Appendix (table A1) which shows comprehensive assessments of the global forests and the annual rate of change from 1990 to 2000 as percentage of forest cover change. In this study 49 African countries were sampled except the islands because they were not within the extracted grid cells of data obtained from MODIS and LPJ-GUESS as such were not used in this study. The FAO data is based on forest inventory data but it is also subject to bias because of inadequate sampling and inconsistent methods as most tropical countries rely on "best guesses" rather than actual field measurements (Gibbs et al. 2007).

2.4. Lund-Potsdam-Jena – General Ecosystem Simulator (LPJ-GUESS)

LPJ-GUESS is a framework for modeling the structure and dynamics of terrestrial ecosystems from global to landscape scales. This model has several modules having formulations of relatively well-defined subsets of ecosystems processes with a spatial and or temporal scale. Figure 3, is a conceptual model describing the processes that occur within the model. The input data are climate parameters (temperature, precipitation, radiation, and atmospheric CO_2 and soil physical properties) which range are daily or monthly values for temperature, precipitation and radiation. The soil properties are used to derive parameters that govern the hydrology and thermal diffusivity of the soil. Photosynthesis, respiration, stomatal conductance are simulated on a daily time step. Individual allocation and growth, population dynamics and disturbance are run on an annual time step.

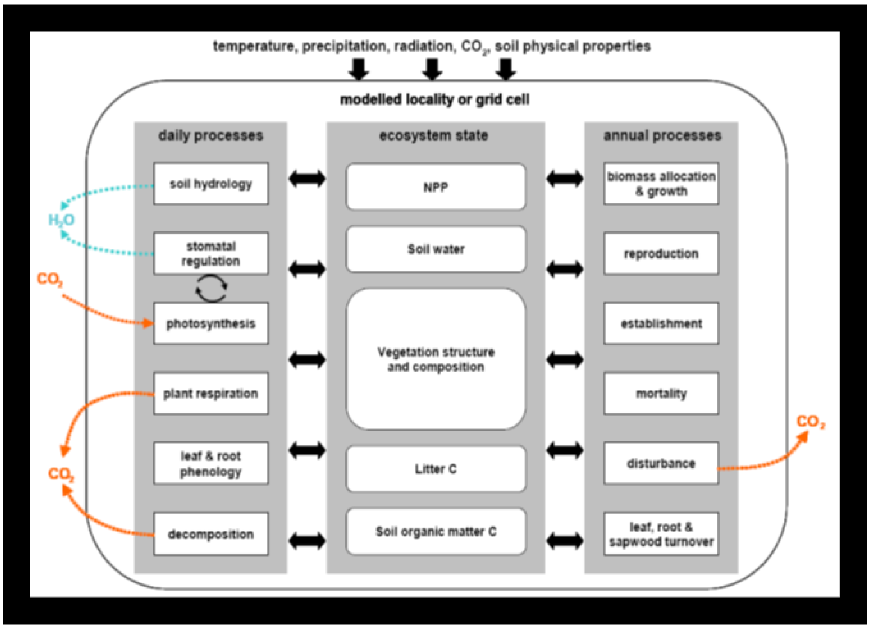


Figure 3. Conceptual model of LPJ-GUESS showing the processes Source: Smith Ben (LPJ-GUESS – an ecosystem modelling framework) as shown in.

Biomass is simulated based on the plant functional types (PFTs) in table.1, which are distinguished according to their bioclimatic niche, growth form woody vegetation (trees) and herbs, leaf phenology (evergreen, summergreen or raingreen).

PFT	Min.coldest month temperature (˚C)	Leaf phenology	Drought tolerance	Shade tolerance	Fire tolerance	Production sensitive to CO_2
TrBE (tropical broad-leaved evergreen tree)	+15.5	evergreen	low	high	low	yes
TrBR (tropical broad-leaved raingreen tree)	+15.5	Drought deciduous	High	High	High	yes
C4G (tropical grass)	+15.5	Drought + winter deciduous	High	Low	High	no

Table 1: Showing the general characteristics of PFTs in Africa. Adapted from Sitch et al. (2003)

PFTs found in Africa as shown in table 1, are tropical broadleaved evergreen tree (TrBE), Tropical broadleaved raingreen tree (TrBR and C4G). TrBR is common in drier areas of the tropics and shed their leaves in the dry season and tropical herbaceous non-woody represents grasses (C4G) which thrive in climates that have a minimum temperature of 15.5˚C or above as parameterised in the LPJ-GUESS model (Sitch et al. 2003; Olofsson and Hickler , 2007). The model was applied to simulate biomass of different PFTs that occur in Africa across grid cells which are independent of each other i.e. the biomass generated for one grid cell does not influence the value of the biomass in the neighbouring cell (Smith et al. 2001; Tang et al. 2010).

LPJ-GUESS simulates biomass as individual demographics (sapling establishment and mortality), carbon allocation through photosynthesis to leaf, root, sapwood and heartwood. Individual tree growth is simulated by regulating the height and the diameter based on the carbon allocation, sapwood conversion to heartwood in a number of replicate patches using a prescribed set of allometric relationships. Disturbances in LPJ are represented with fires and random patch destruction with a 0.01 probability of its annual occurrence which correspond with natural hazards such as insect attracts (Smith et al. 2001; Tang et al. 2010).
Human induced conversion is not represented in LPJ-GUESS (Tang et al. 2010). The proposed simulation in this study was to establish biomass. Simulation occurs in phases, it begins with bare ground which implies the area being modelled has no vegetation (spin up phase) to establish vegetation, litter and soil carbon pools at equilibrium with long-term average climate. A historical phase using observed climate as input data. A detailed description of the model is available in (Smith et al. 2001; Sitch et al. 2003).

3. Methods

This study examined the spatial and temporal trend of biomass in Africa on a continental, regional and country scale, to estimate the quantity of biomass held in Africa assuming the rate of forest cover change remained constant. The regional division scheme defined by the United Nations (UN) statistics division (2011) was used in grouping countries into five regions, to estimate the quantity of biomass held by each African region. FAO (2003) data on forest cover change for year 1990 - 2000 was used to assess the effect forest cover change had on biomass. The vegetation type was not considered; the focused was on biomass change for the entire region for the study period 2001 – 2030. The forest area in Djibouti, Gabon (within the Congo basin), Gambia, Lesotho, Morocco and Western Sahara did not experience any significant rate of change (n.s.) as stated in the FAO (2003) report as such the data for these countries showing their rate of change was replaced with the number one. As such when computing for change in biomass, the difference would be zero because the observed change was negligible.

The study design involves two phases for data. The first phase is data collection on deforestation rates for the continent on a country-specific basis and assimilation. The data is re-gridded and appropriate indices are extracted at the continent level from longitudes 17.52°W through 51.38°E and from latitudes 37.34°N through 34.80° S with a resolution of 1°x1°cell size. The second phase involves overlay analysis and descriptive statistics to find out how deforestation rates affect carbon stocks and the associated trends in Africa over a 30 year period.

Biomass (kg C/grid cell)

The biomass was simulated across 2548 grid cells obtained from MODIS VCF percent tree cover (%) and LPJ-GUESS (kg C). MODISVCF data had percent tree cover for Africa in the same latitude and longitude as the biomass from LPJ-GUESS, because MODIS VCF was re-gridded to 1 degree. Deforestation rates based on the change in forest cover per country from FAO (2003) was applied assuming the rate of deforestation remained constant during the study period (2001 – 2030).

The estimated biomass was calculated by multiplying LPJ-GUESS biomass (kg C) by percent tree cover from MODIS VCF. The output which is estimated biomass per grid cell is multiplied by the deforestation rates as given by FAO (2003) to obtain the potential biomass held in trees in Africa from year 2001 – 2030.

The equations below shows how biomass was computed for the continent

Actual Biomass (kg C) = (percent tree cover x biomass) /100 * surface area of a grid cell (1)

The units of biomass were divided by 1000 to convert to (tons C/grid cell)

Area of a grid cell was calculated using the equation below:

Surface area of a grid cell = R^2 ($\lambda 2 - \lambda_1$) ($\sin\varphi_2 - \sin\varphi_1$) (2)

Where:

R – Radius of the earth (6371km)*1000 to convert to meters

λ – Longitude expressed in radians

φ – Latitude expressed in radians

The difference between each grid cell is 1degree

The source for the above equation is (The British Atmospheric data Centre
, 2002).

Deforestation rate (%) as shown in Appendix A (Table A1) which is country specific was calculated to get the actual rate of change for tree cover based on the assumption that a decline in tree biomass implied an increase in grass biomass.

Change in carbon stock per year (tons C)

Biomass change was computed as the difference between the present and previous time step (e.g.Y_{t2}-Y_{t1}).

Deforestation rate was applied to each grid cell (trees) that was found within a given country. In this study biomass loss from African vegetation due to deforestation was disaggregated among 49 African countries (Appendix A, Table A1) based on biomass obtained from LPJ GUESS, percentage vegetation cover from MODIS VCF and deforestation rates from FAO. The study is expected to generate outputs that broadly capture temporal and spatial trends of carbon stocks in Africa.

3.1. Geographic Information System Tools and Data

The data was summarised on a region and country by country basis for spatial analysis. Overlay operations were performed after the data sets were all re-gridded to 1x1 degree resolution. The annual rate of change of biomass for each country was computed for each grid cell and this was calculated by multiplying the actual biomass per grid cell (kg/yr.) with the annual rate of change e.g. (2001 + change in biomass = biomass for 2002, with the assumption that forest cover change (from FAO from 1990 – 2000) remained constant over the period being studied.

This research measures loss of carbon from trees based on deforestation rates, the area previously and presently occupied by vegetation and the area of remnant biomass if the deforestation rates prevail at the 2001 rate based on FAO data. Spatial analysis using the overlay operation was the prominent tools used in this study. The GIS software used was ArcGIS 9.3, with reliance on raster overlay and modelling capabilities of the Grid module; also vector data of 2548 points of biomass extracted from LPJ-GUESS within the above mentioned countries in Africa were re-gridded to 1^{o} x 1^{o} cell size and projected using the geographic coordinate system WGS84, Prime meridian: Greenwich; Angular unit: Degree; the projected coordinate system is WGS84 PDC Mercator; projection: Mercator; False easting 000, central meridian -15000, standard parallel 1:0 00 linear unit: Meter.

Total biomass for the continent was calculated as the sum of tree and grass biomass.
However, tree biomass was simulated using the change in tree biomass in Appendix table A1.
Grass biomass was simulated with the assumption that a decline in tree cover would increase the grass cover which in turn would generate an increase in grass biomass.

4. Results

4.1. Spatial and temporal distribution of Carbon stocks in Africa.

4.1.1. Total carbon stock

Maps for the total amount of carbon stock during the period 2002 to 2030 are presented in Figure 4 below. It is projected that for the 49 countries sampled, the total carbon stock for the continent is increasing mainly due to an increase in grass biomass (see below). Appendix A (table A1) shows forest deforestation rate according to countries, negative values indicate a loss in forest cover and the positive values indicate a gain in forest cover for some African countries. Figure 4 below shows potential estimates of total biomass and changes in total biomass for years 2002, 2015 and 2030.

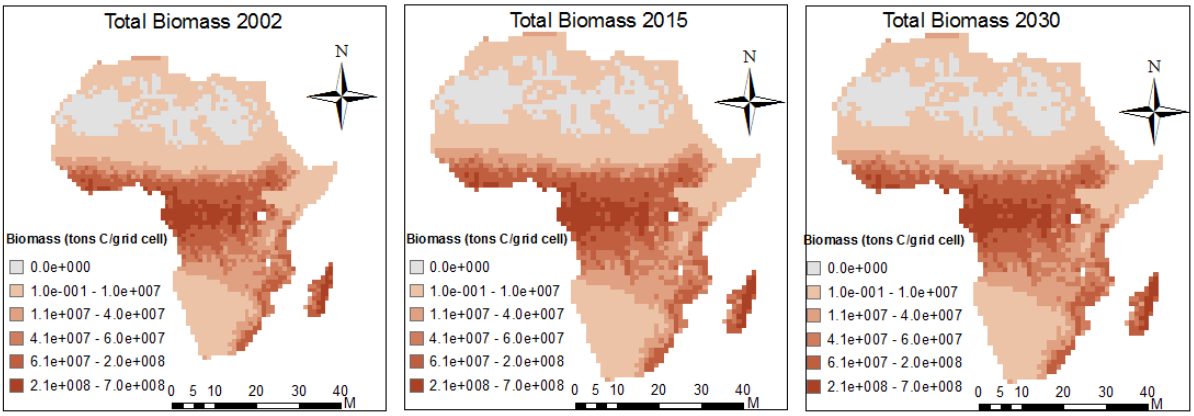


Figure 4. Total biomass (tons C /grid cell) at 1x1 degree cell size resolution.

Most of the biomass on the continent is concentrated along the coasts of West Africa, Madagascar and the Congo Basin. There is an observed increase total carbon stock. Total biomass increased from 2002 to 2030 mostly along the coast of Western and Eastern Africa but this is not very visible in figure 4 above but in Appendix table A2, the changes can be seen. The observed change in biomass for the 49 countries shows a slight increasing trend in most of the African countries as can be seen in Appendix table A2. Change in biomass is positive for most countries but some countries such as Burundi, Gambia and Liberia experienced a negative change in biomass. More details on biomass change on a country-specific basis are presented in Appendix table A4.

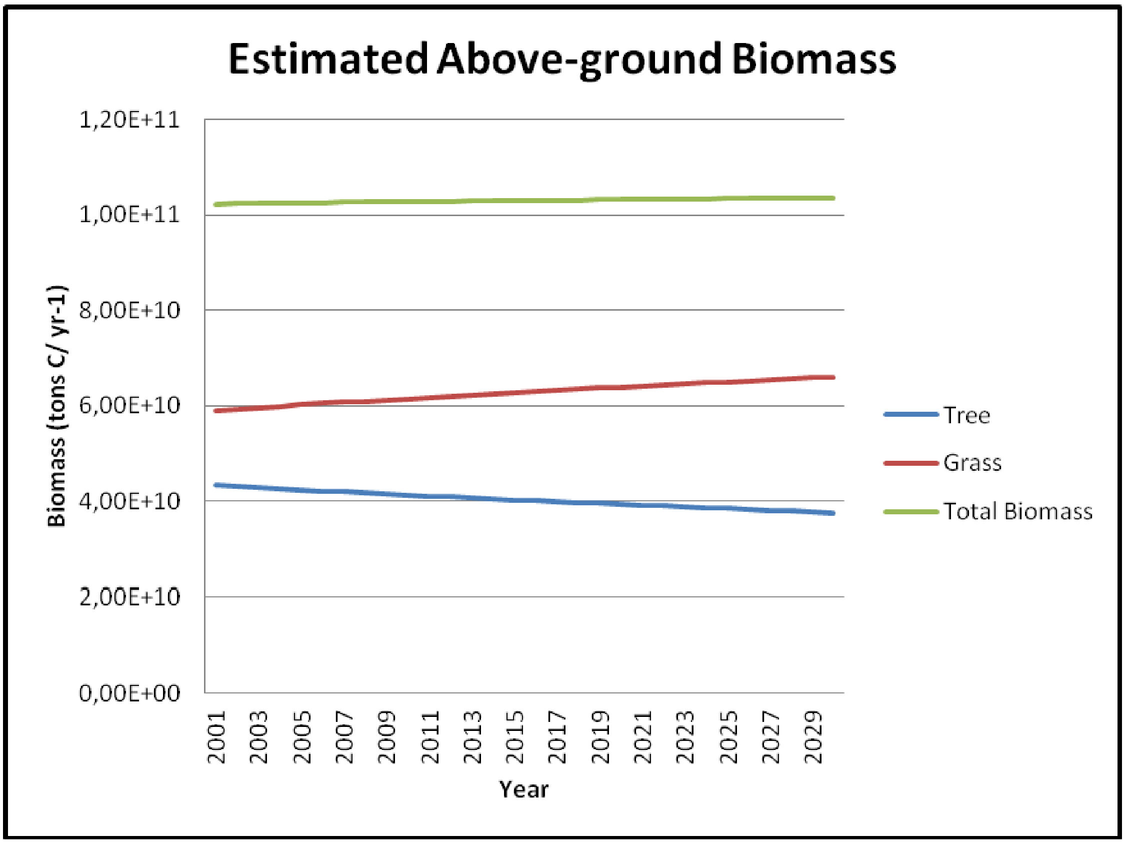


Figure 5. Trend of estimated annual total biomass, tree biomass and grass biomass from the period 2001 – 2030.

The linear trends for biomass in figure 4.2 show that this study projects a slight increase in annual total biomass during the study period. As shown in figure 5, the total biomass is expected to increase from about $1.02x10^{11}$ – $1.04x10^{11}$ (tons C/yr^{-1}), tree biomass is expected to decline from about $4.32x10^{10}$ to 3.76 $x10^{10}$ (tons C/yr^{-1}) while grass biomass is expected to increase from 5.9 $x10^{10}$ to 6.60 $x10^{10}$ (tons C/yr^{-1}). More information is available in the Appendix (Table A2).

4.1.2. Region-specific total carbon stock

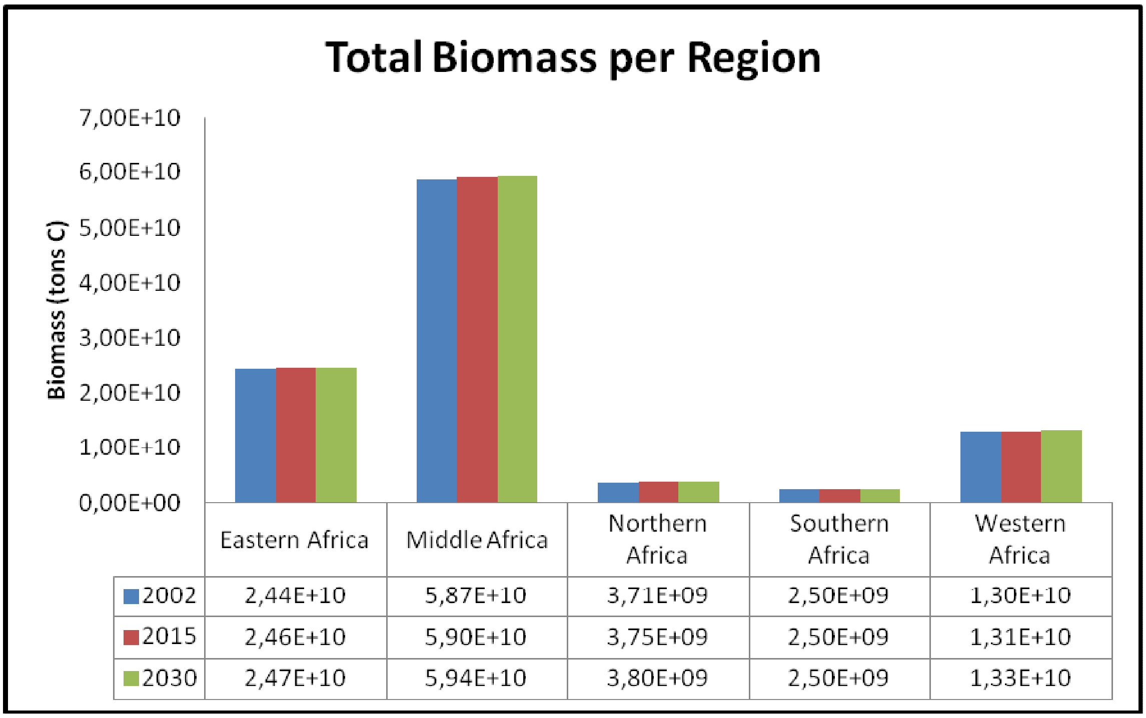


Figure 6a. Total of biomass per region.

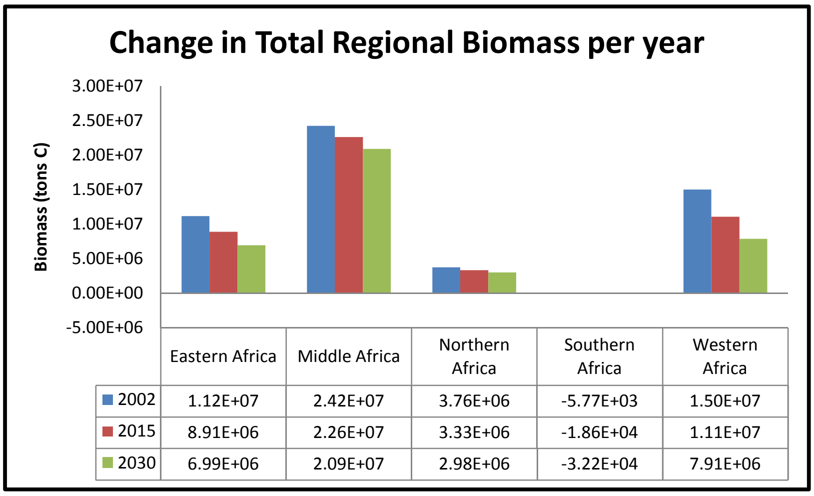


Figure 6b.Change in biomass per region per year.

To investigate regional biomass trends, biomass aggregated in 49 countries was summed and grouped into regions according to the United Nations Statistics Division. As shown in figure 6a, predicted regional biomass increased for all African regions except Southern Africa where the total biomass was fairly constant. Most of the biomass in the region is concentrated in Middle Africa. Northern and Southern African had less biomass as compared to other regions. The projected increase in total biomass in Middle Africa as shown in figure 6a was from about 5.87 x 10^{10}, 5.90 x 10^{10} and 5.94 x 10^{10} (tons C) in 2002, 2015 and 2030 respectively. Change in biomass as shown in figure 6b, indicates that all regions had positive changes in biomass except Southern Africa that had negative changes in biomass. The period with the highest change in biomass was 2002 and by 2030 although there is an observed change in biomass, the quantity is reduced as compared with 2002. This feature stems from the fact that a constant rate of change was applied. The region having the highest positive change in biomass was Middle Africa with 2.42 x10^7 tons C.

4.1.3. Country-Specific Total carbon stock and changes

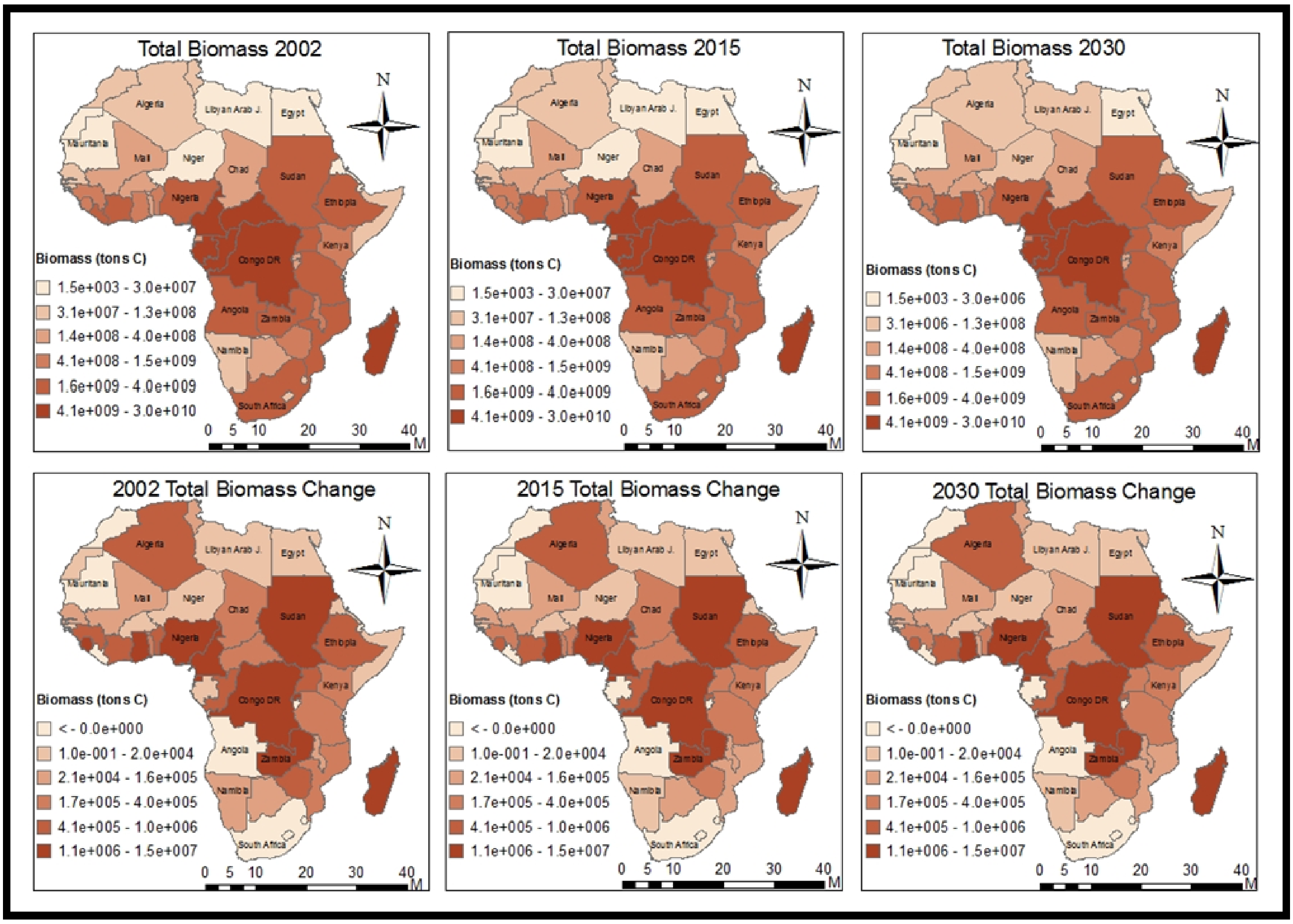


Figure 7. Country-specific carbon stock and changes for year 2002, 2015 and 2030.

Figure 7 shows that most of the biomass as mentioned earlier is concentrated in the Congo Basin, Madagascar and the coast of western Africa. Some countries with very high total biomass estimates for year 2002, 2015 and 2030 respectively are Dem. Republic of Congo (2.9x10^{10}, 2.93x10^{10} and 2.95 x10^{10} tons C), Congo (9.06 x10^9, 9.07 x10^9 and 9.08x10^9 tons C), Madagascar (8.41x10^9, 8.45 x10^9 and 8.50x10^9 tons C), Gabon (6.56 x10^9, 6.56x10^9 and 6.56 x10^9 tons C), Cameroon (5.20x 10^9, 5.28 x 10^9 and 5.37 x 10^9 tons C). Algeria, Eritrea, Niger, Liberia and Libyan Arab Jamahiriya had spatial and temporal changes in total biomass as well as shown in figure 7.

There is an observed change in total biomass in all the African countries as indicated in figure 7. Countries that experienced high changes in total biomass for years 2002, 2015 and 2030 were Democratic Republic of Congo, Nigeria, Cameroon, Zambia and Madagascar. Egypt, Tunisia, Libyan Arab Jamahiriya and Algeria all experienced increasing changes in total biomass while Mauritania, Burundi, Gambia, Swaziland, South Africa, Angola and Liberia had negative changes in total biomass. More results are presented in appendices Table A4.

4.2. Total Tree carbon stock

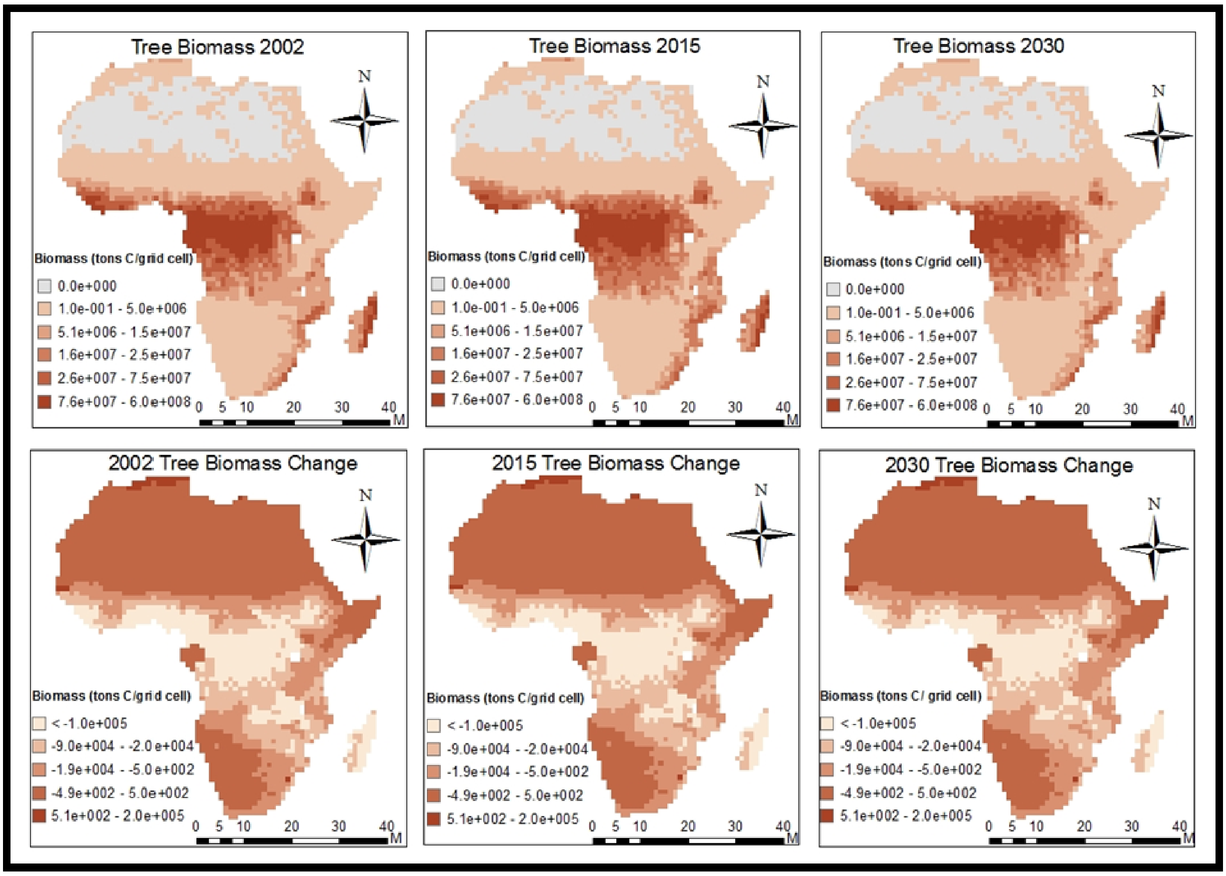
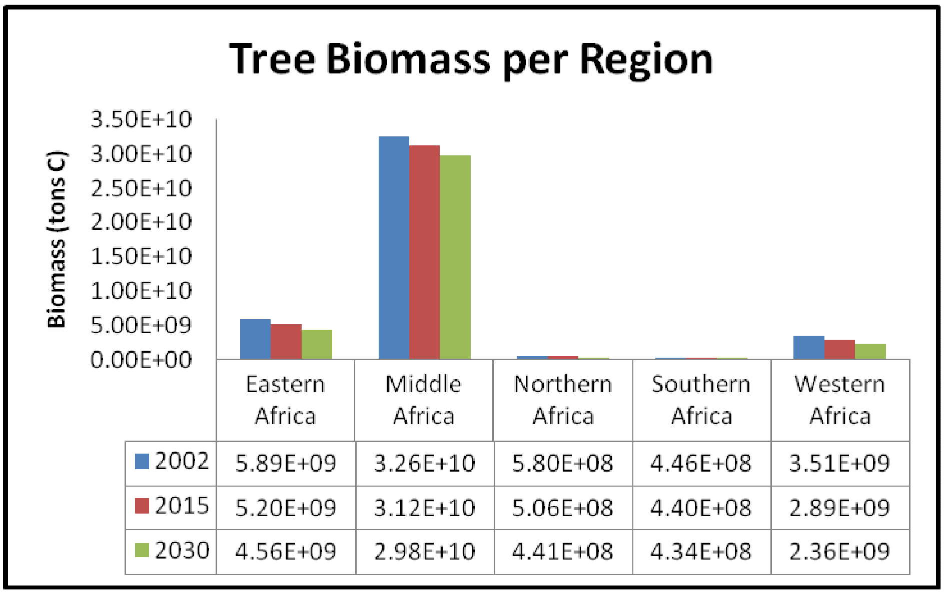


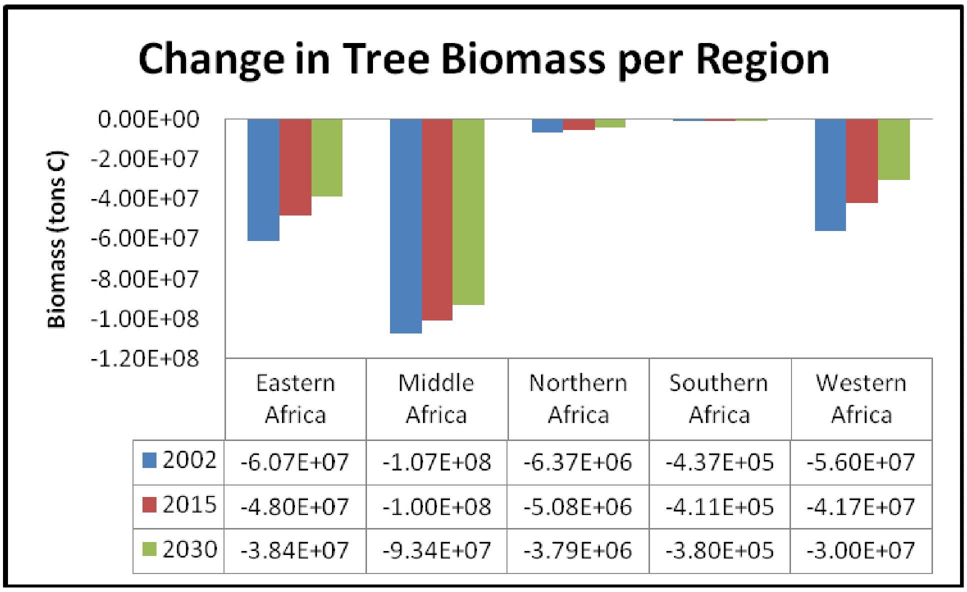
Figure 8. Total tree biomass and change in tree biomass (tons C/grid cell).

Figure 8 shows the spatial and temporal trends in tree biomass, with decreasing biomass for the period under projection. Tree biomass was computed based on the rate of change of forest cover shown in Appendix table A1. The cells having grey colours have zero tree biomass and are located in Northern Africa mainly around the Sahara desert. The countries that had a positive change in forest cover are Algeria, Egypt, Gambia, Libya, Swaziland and Tunisia. Tree biomass is dominant around the Congo basin, the coast of West Africa and Madagascar. Massive decline in tree biomass occurred in countries having dense vegetation cover such as Madagascar and the Congo basin. Tree biomass declined greatly in 2002 and although there is a noticeable decline in 2015 and 2030 but the quantity of biomass lost to deforestation in years 2015 and 2030 was less as compared with year 2002, because the rate of change applied would yield a decrease in tree biomass because the rate of change is a decrease. Tree Biomass annually declined from about 4.3 $\times 10^{10}$ tons C in 2002 to 3.8 $\times 10^{10}$ tons C in 2030. Annual changes in tree biomass are -2.31 $\times 10^{8}$ tons C in 2002 and -1.66 $\times 10^{8}$ tons C in 2030 are presented in Appendix A table A5. Changes that lead to a loss in tree biomass as presented in figure 8 can be seen in the Congo basin and Madagascar during the study period.

4.2.1. Tree carbon stock per region.



9a.Tree biomass per region



9b. Change in tree biomass per region

Figure 9a and 9b displays the estimated tree biomass and changes that occurred per region during the study period. The Middle African region has the highest estimate of biomass with little decline as shown in figure 9a. Southern Africa and Northern Africa have the lowest estimates of tree biomass. Figure 9b (estimated changes in tree biomass) shows that all regions had negative changes with Middle Africa recording the highest loss in tree biomass during the entire projection period. Southern Africa had the least change in tree biomass.

4.2.2. Country-specific tree carbon stock.

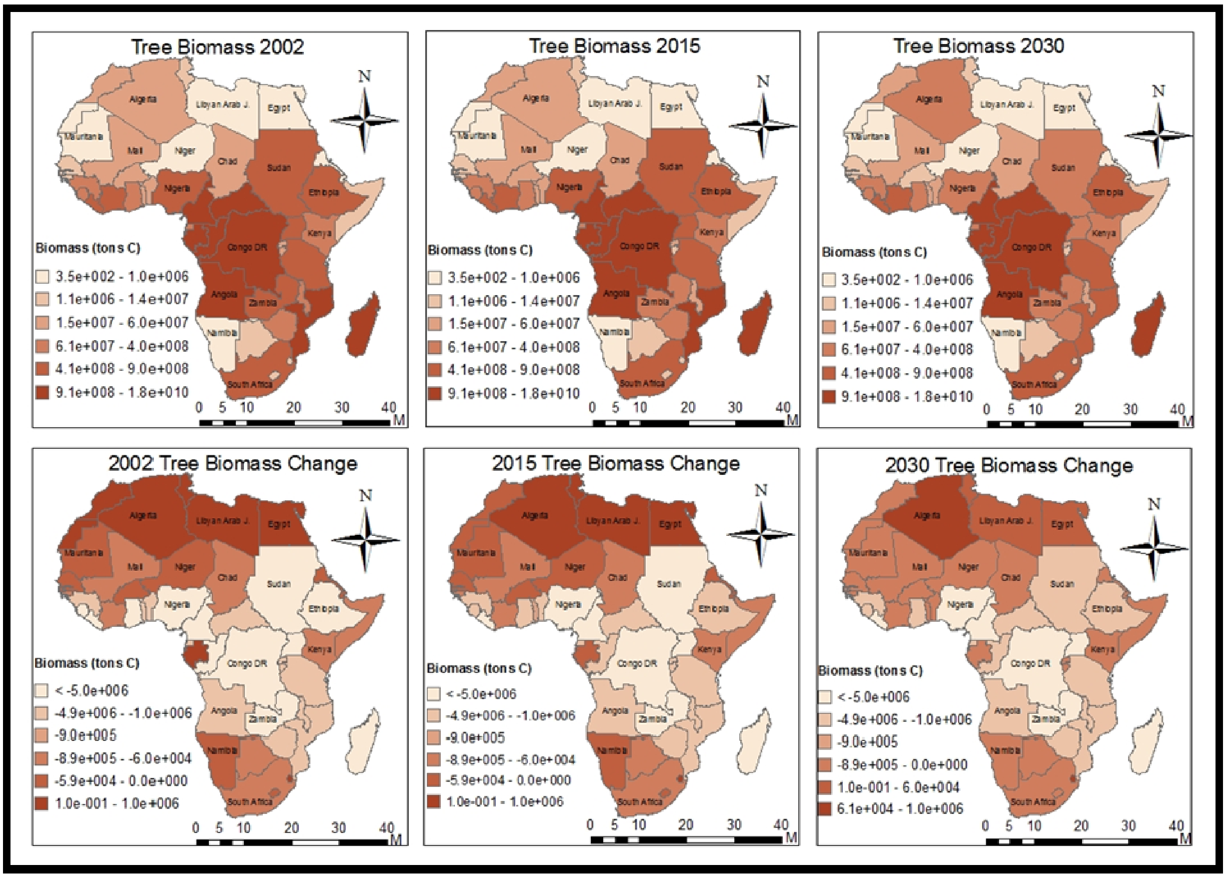


Figure 10. Country-specific tree biomass and changes in tree biomass (tons C).

Spatial and temporal analysis of country-specific tree biomass for years 2002, 2015 and 2030 is shown in figure 10. Tree biomass is concentrated in countries located in the Congo basin and Madagascar. Northern African countries are projected to have a positive changes in tree biomass according to figure 10. From year 2002 onwards high decline in tree biomass is projected in most countries. Appendix A, table A6 has more results on tree biomass with its associated changes on a country-specific basis.

4.3. Grass carbon stock

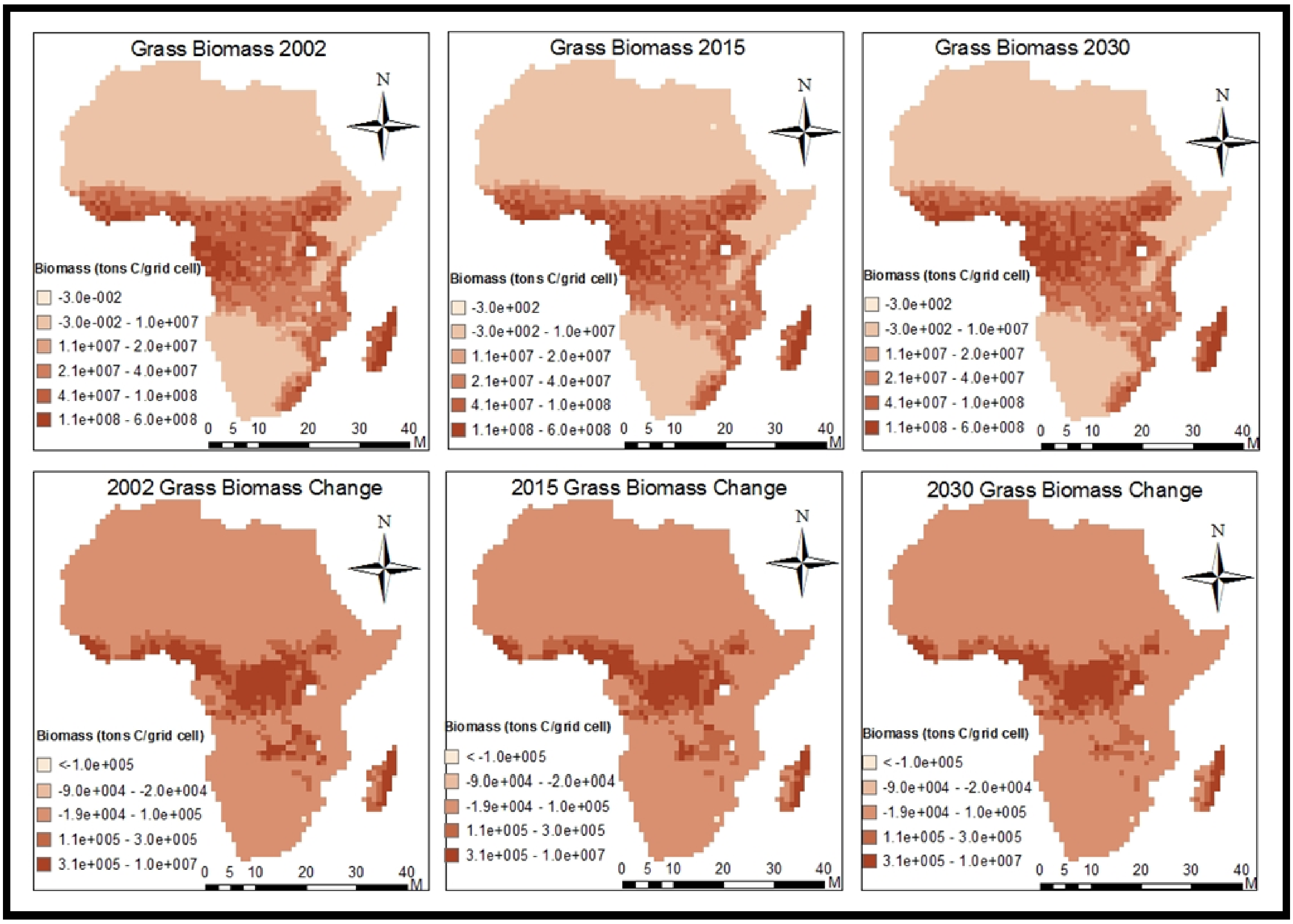


Figure 11. Spatial and temporal distribution of grass biomass in Africa.

Projected distribution of grass biomass is presented in figure 11. Grass biomass was computed with rates of change in forest cover for all 49 African countries as presented in Appendix table A1. Annual sum of grass biomass in 2001 is 5.9 x 10^{10} and 6.60 x 10^{10} in 2030. More results on annual grass biomass can be seen in appendix A table A7. Grass biomass is concentrated along the coast of West Africa, the Congo basin, Madagascar and along the coast of Mozambique. The spatial and temporal trend in grass biomass is antagonistic to tree biomass since there is a projected increasing trend in grass biomass on the continent and a decline in forest biomass. The projected loss in tree biomass is assumed to lead to an increase in the area covered with grass biomass; the loss in the area once covered by forest is added to the area covered by grasses. Changes in grass biomass in fig. 11 are concentrated in areas that have dense tree biomass such as along the coast of West Africa, Madagascar and most of the Congo basin.

4.3.1. Grass carbon stock per region

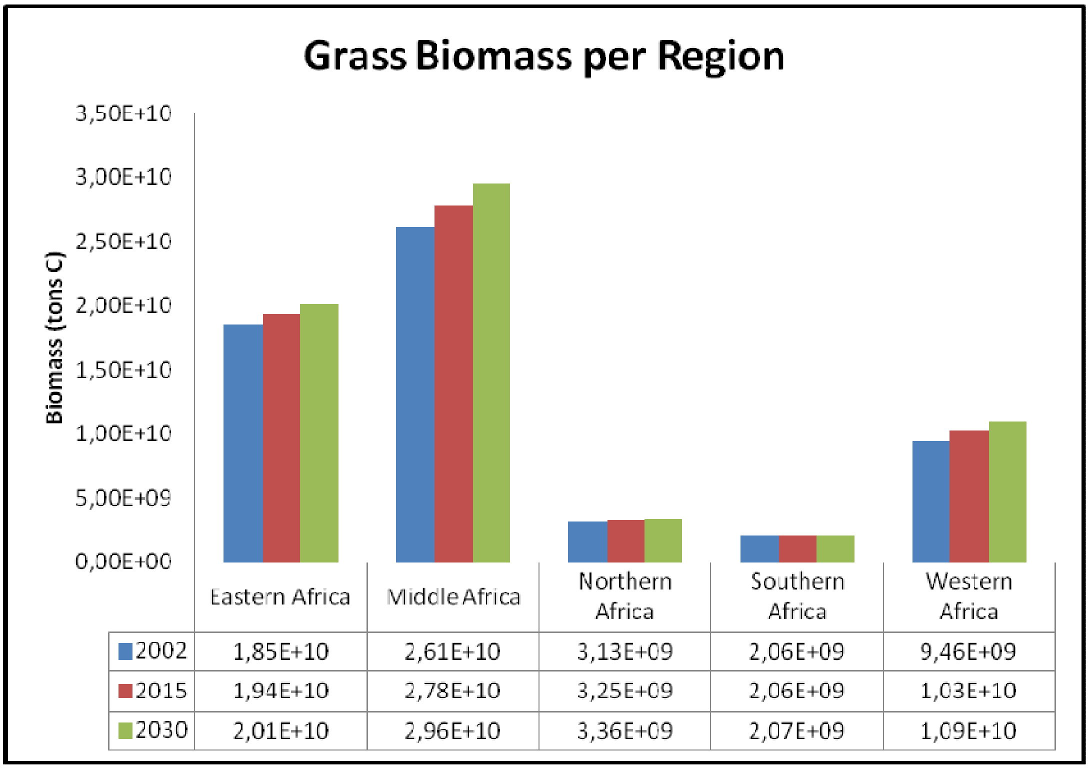


Figure 12a. Grass per region per region

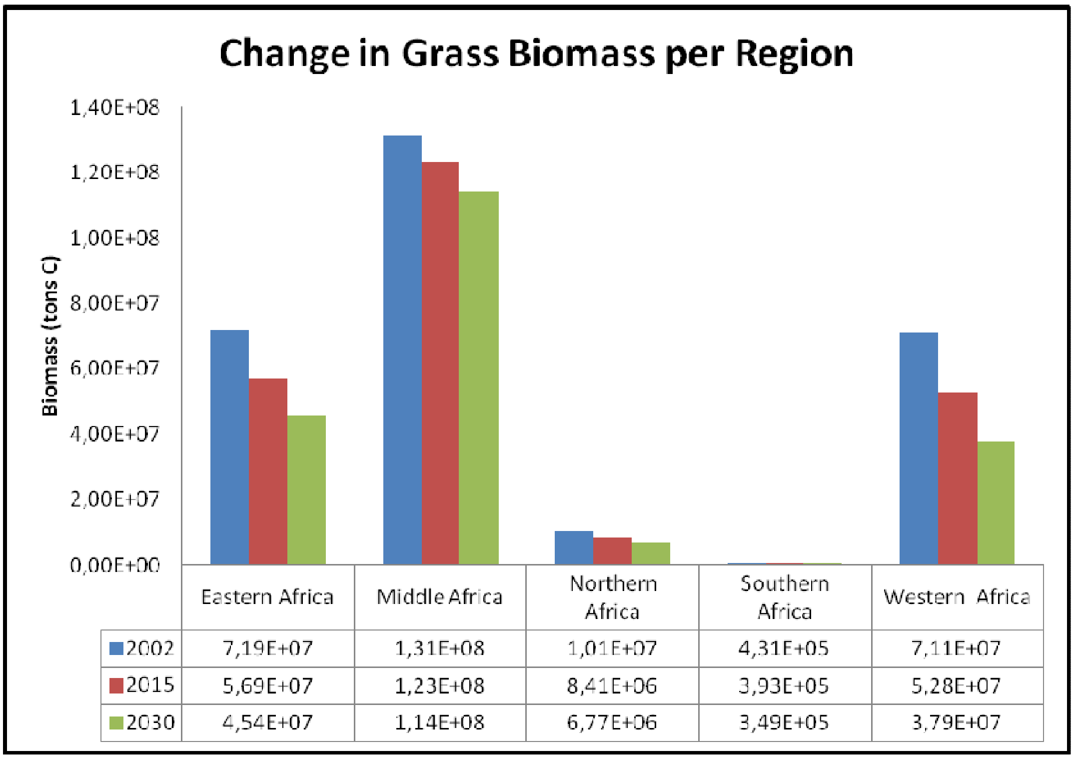


Figure 12b. Change in grass biomass per region

Figure 412a and 12b show grass biomass trends with most of the grass biomass located in Middle and Eastern Africa, Southern Africa has the least in grass biomass amongst the regions. There is an overall increase in region- specific biomass from 2001 to 2030 as shown in figure 12a. Changes in grass biomass for all regions are positive.

4.3.2. Country-specific Grass carbon stock

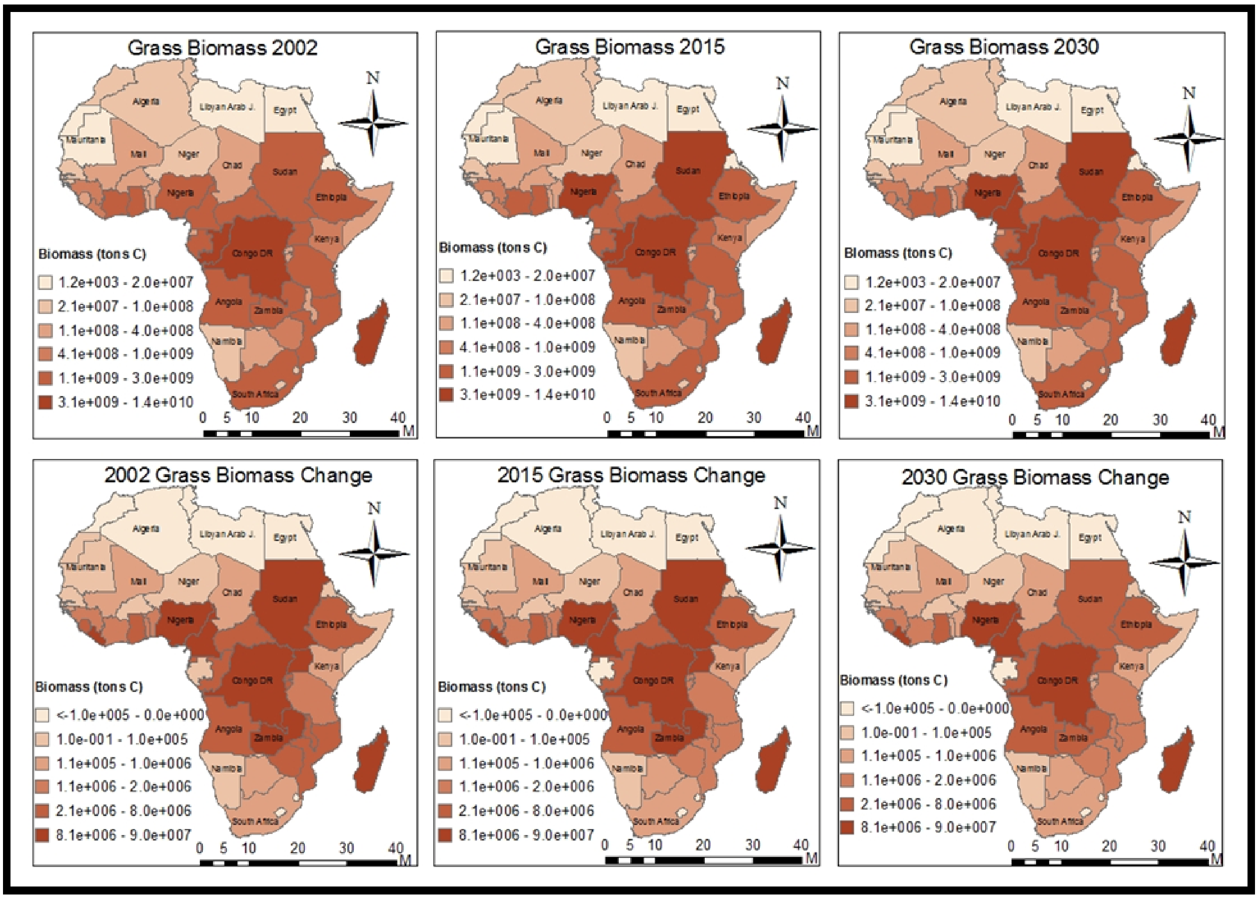


Figure 13. Country-specific grass biomass.

Biomass in grasses increased all through the period under investigation in most African countries as presented in figure 13. Dem. Republic of Congo, Madagascar, Congo, Sudan and Nigeria had high estimates of grass biomass as compared to other. The countries with the least grass biomass estimates are Western Sahara, Djibouti, Egypt, Mauritania and Libyan Arab Jamahiriya. Country-specific grass biomass projections as presented in fig. 13 show that Nigeria, Cameroon, Sudan, Democratic republic of Congo and Madagascar have positive and high changes in biomass. Countries with no change are Gabon, Western Sahara, Lesotho, Djibouti and Morocco. A decline in grass biomass is projected in Swaziland, Algeria, Gambia, Tunisia and Libya Arab Jamahiriya. More details are presented in (Appendix table A8 on country specific biomass and changes).

5. Discussion

5.1. Spatial and temporal distribution of carbon stocks in Africa

5.1.1. Total carbon stock in Africa

The concentration of most of the biomass estimates in Africa is in the Congo basin as found in this study (figures 4 and 7) are consistent with previous studies on spatial distribution of biomass. FAO (2000) report on global forest resource assessment showed the spatial distribution of biomass in Africa for the period 1990 - 2000. Houghton (2005) found that the average above ground forest biomass for Africa increased in the 1990s. However, Houghton's study did not define biomass as grass or tree but rather the total above ground biomass was considered. Biaccini et al. (2008) conducted a study on the spatial distribution of above ground biomass in Africa from 2000 – 2003 and observed that most of the biomass is concentrated in the Congo basin and fragments of forest biomass is found along the coast of West Africa. This study has projected an increasing trend (though very slightly) in above ground biomass in Africa for the study period 2001 to 2030 (Appendix table A2).

Several studies carried out on Africa carbon stock, e.g. estimation by Ramankutty et al. (2009), William et al. (2007), Melillo et al. (1996), and Houghton (2005). Gibbs et al. (2007); mentioned that the flux of carbon to the atmosphere due to land use change in Africa ranges from 3.50 x 10^8tons C yr^{-1} – 3.94 x 10^8 tons C yr^{-1} from 1980s to the 1990s. This study considered only above ground biomass (trees and grasses) and projected positive changes in total carbon stock from 5.42 x 10^7 tons C in 2002 to 3.87 x 10^7 tons C in 2030. The predicted estimates of carbon fluxes in this study differ from other studies due to the difference in the applied methods. We also only took the above ground biomass into account, while the fluxes generated by the other studies are based on both above and below ground biomass.

More results of the projected changes in total above-ground biomass can be seen in (Appendix A table A2). Most of the biomass as confirmed by Biaccini et al. (2008) is located in western Africa, the Congo Basin and Madagascar. However, studies by Houghton (2005), Gibbs et al. (2007) and William et al. (2007) mentioned that measuring estimates of biomass in Africa is challenging due to the lack of accurate data and the use of obsolete data collection techniques. The spatial and temporal trend of increasing total biomass for Africa can be attributed to an overestimation of grass biomass by LPJ-GUESS which simulates biomass based on environmental factors and climate variables; Weber et al. (2009) in their study mentioned that Africa is a water deficient continent and LPJ-GUESS simulates high grass biomass in water stressed regions. FAO (2010) mentioned that Africa biomass declined from about 6.10×10^{10} in 1990 to 5.8×10^{10} in 2000 and 5.5×10^{10} tons C for 1990, 2000 and 2010, which seems to be more reasonable than the modelled results of this study. The predicted trend of biomass in Africa (figure 4 and 5) is an increase, which ranged from 1.02×10^{11} to 1.04×10^{11} tons C in 2001 and 2030 respectively. However, though the total biomass might be overestimated due to the modelling of the grass biomass, the results concerning the loss of tree biomass are still in the range of the literature mentioned above.

5.1.2. Region specific total carbon stock

Most of the regions showed variations in the increasing estimates of biomass (figure 6a & 6b); this can be explained by the amount of biomass held in each region, the prevailing climate and the type of vegetation found in these regions. This study estimated that the total biomass for Southern and Northern Africa is low as compared to Eastern, Middle and Western Africa, this finding was corroborated by FAO (2000). This increase in biomass in southern African can be attributed to climate variations in the region (Kalwij et al. 2010). Vegetation holds most of the carbon as compared to the atmosphere according to FAO (2010). This study shows in figure 4.3a that most of the biomass is located in regions that are rich in forest cover. Southern Africa has the least estimate in total biomass for the study period. FAO (2010) also stated that most of the projected total biomass is found in Western and Middle Africa while this study observed that most of the total biomass located in Eastern and Middle Africa this can be attributed to the grouping of Madagascar into the Eastern Africa region.

5.1.3. Country-specific total carbon stock

Assessing country-specific biomass and the changes predicted due to change in forest cover (Figure 7 and Appendix table A3) indicate that the Dem. Republic of Congo had a decline in biomass from 2001 through to 2030. The decline in biomass in Middle Africa is also mentioned in the study conducted by Zhang et al. (2002) and FAO (2005). Zhang et al. (2002) conducted their study in Middle Africa using the drivers of deforestation such as population growth and agriculture to assess the impact of shifting cultivation on carbon stocks and subsequent emissions of carbon due to deforestation. Their study found that in 1950, shifting cultivation accounted for emissions of about 15% from aboveground biomass, with the assumption that the area was occupied by dense forests. Due to projected populations estimates they observed that the remaining above ground biomass would be about 40% in 2050. Carbon uptake from fallow lands and secondary forests was projected to increase by an average of 0.4 tons/ha in 1950 to 3.4 tons / ha in 2050 which suggests that the uptake could compensate for the losses. FAO (2005) mentioned that the amount of biomass in western and middle Africa declined from 4.6×10^{10} tons C in 1990 to 4.39×10^{10} tons C in 2000 and 4.31×10^{10} tons C in 2005. The drivers of deforestation were not considered in this study. The countries with the most total biomass are found along the coast of western Africa, the Congo basin and Madagascar. Quantifying the amount of vegetation biomass stored, lost or gained due to change in forest cover is important in estimating the actual amount and changes in fluxes of carbon within any given ecosystem (Zhang et al. 2005). All countries had positive changes in total biomass except Liberia, Angola, South Africa, Swaziland and Gambia. The different results between this study and the results obtained from other studies can be attributed to the type of data used, the area being studied such as the entire African continent as compared with the Congo Basin and the method of data analysis. Brown and Gaston (1995) observed that the potential biomass estimates from African countries located in Western Africa to Middle Africa was high while Botswana, Niger and Somalia has low biomass estimates. The countries with predicted estimates of high total biomass are Dem. Republic of Congo, Madagascar, Congo, Gabon and Central African Republic and low biomass estimates are Western Sahara, Djibouti, Egypt, Mauritania and Libya Jamahiriya Appendix table 3. The estimates of total biomass for Western Sahara and Djibouti remained constant because the change in forest cover was insignificant. These studies confirm the uncertainties associated with the role Africa plays in the global carbon budget (William et al. 2007). Projections made in this study indicate that densely forest areas are more likely to be affected by deforestation as compared to other vegetated surfaces which is confirmed by studies conducted by Gibbs et al. (2007).

5.2. Tree carbon stocks

Most of the biomass found in Africa is held in trees as presented in figure 8. Trees help mitigate climate change by sequestering carbon (Gibbs et al. 2007; William et al. 2007; Bombelli et al. 2009; Neufeldt et al. 2009). According to the review by William et al. (2007), plants hold about $8x10^{10}$ tons C, of which, according to this study tree biomass hold about 4.32 x 10^{10} tons C and the remaining is held in grass biomass. The estimates of the sum of biomass found in grasses and trees are within the range of biomass held in plants according to Williams et al. (2007).

In this work, tree biomass is dense along the coast of Western Africa, the Congo basin and Madagascar as shown in figure 8. This is confirmed in the study by Gibbs et al. (2007) which was a comparison of various carbon pools in tropical ecosystems. Change in tree biomass ranged from -2 .$3x10^8$ tons C yr^{-1} in 2001 and -1.66 x 10^8 tons C yr^{-1} in 2030 as can be seen in figure 8 and appendix A (table A4). William et al. (2007) in their review estimated that about $3.7x10^8$ tons C had been lost to deforestation in Africa during the last decade. The amount of tree biomass estimated to have been lost to deforestation is -2.31 x 10^8 and $-1.66x10^8$ tons C in 2002 and 2030 respectively. The amount of tree biomass lost to deforestation declined which can be attributed to the constant rate of deforestation applied in this study. Ciais et al. (2009), using the vegetation model (ORCHIDEE) estimated that the carbon flux to the atmosphere from deforestation was 1.3 $x10^8$ tons C for the 1990s. William et al. (2007), Houghton (2005) and Bombelli et al. (2009) mention that Africa has a neutral carbon balance and could be a potential carbon sink or source and this study also only found very low differences in total carbon balances and hence could not categorically state Africa's role in the global carbon cycle either as a sink or source of carbon.

5.2.1. Regional tree carbon stock

The regional estimates of tree biomass as shown in figures (9a and 9b) indicate that all regions had a projected a decline in tree biomass from 2001 to 2030 and this would mean an increase in grass biomass for the regions as well. The decline projected in regional tree biomass could be attributed to the forest area loss. This is confirmed by studies conducted by Zhang et al. (2005) in Middle Africa and the effect of deforestation on forest biomass. Southern Africa holds the least biomass in tree. The changes in tree biomass predicted that Middle Africa lost about -1.07 x 10^8 tons C to deforestation in 2002 and findings from FAO (2005) confirm this that biomass in forested regions in Africa experienced a decline.

5.2.2. Country-specific tree carbon stock

Most of the tree biomass on the African continent is found in the countries situated in the Congo basin and the coasts of Western African and Madagascar. According to FAO (2010) estimated annual change in forest biomass in most Africa countries was not significant as shown in figure 10 and Appendix A5, this study confirms this projected decline. Countries with dense tree biomass had a decline in tree biomass which corroborates the observation by William et al. (2007) and Gibbs et al. (2007) that regions with dense vegetation cover are prone to being converted to other land uses.

5.3. Grass carbon stock

The spatial distribution of grass biomass in Africa (figure 11 and appendix table A6) is higher than tree cover in the savannah regions. This increase in potential grass biomass can be attributed to the decline in forest cover, thereby leading to this striking result. According to Julia States (2005)'s study on temporal and spatial variations of surface albedo in Africa, a decline in vegetation (trees) would result in an increase in surface albedo subsequently leading to reduction in precipitation. This study observed an increase in grass biomass from 5.9x 10^{10} tons C to 6.6 x 10^{10} tons C in 2001 and 2030 respectively. In reference to Julia States (2005) this could lead to a decline in precipitation pattern and adversely affect the sequestration of carbon from the atmosphere thereby altering the global carbon cycle. This study assumed a decline in tree biomass would lead to an increase in grass biomass which may outweigh the tree biomass but in reality this may not be the case as a decline in tree biomass may not lead to an increase in grass biomass because an area once forested can be cleared for construction purposes. Increasing grass biomass in Africa could bring about the increase of extreme climate events such as drought on the continent.

5.3.1. Grass carbon stock per region

Regional grass biomass shows that most of the grass biomass is found in Eastern and Middle Africa (figure 12a). This increase in grass biomass for this region can be attributed to forest cover being converted to grassland. The services provide by trees in sequestrating carbon is reduced with increase in grass biomass (Hansen et al. 2003), though this is contradictory to the modelling of this study, I consider this reasonable. Southern and Northern Africa had an increase in grass cover but it was low compared with the other regions. Estimated changes in grass biomass (figure 12b) indicate that in 2015 and 2030, Eastern Africa and Middle Africa have a high grass biomass as mentioned in FAO (2010) state of the world's forest. Climatic variation and increase in the land use change (Melillio et al. 1996; Candell et al. 2009) can lead to increase in grass biomass as observed in this study. The conversion of forested area for agricultural purposes is prevalent in these regions. Change is grass biomass for all regions is highest in year 2002 due to change in forest cover. Forest cover change remained constant for the period under investigation and this is not realistic. Hence the findings that recorded the highest loss in tree biomass due to decline in forest cover in the first year are considered to be artificial.

5.3.2. Country-specific grass carbon stock

The spatial distribution of grasses in Africa countries as shown in (figure 13 and Appendix A table A7) indicate that countries that had increase in forest cover experienced declining grass biomass as expected. Algeria, Egypt, Gambia, Libya, Swaziland and Tunisia all had declining projected grass cover due to increase in tree cover but the type of vegetation in the region and the prevailing climate does not necessarily suggest that there was a decline in grass biomass. (FAO 2005) gave an in-depth description of the dominant vegetation types found in each country of Africa.

5.4. Limitations of this study

The data used in this study especially the FAO based deforestation rates on estimated forest cover changes from countries are unreliable in some areas since the data is either obsolete or based on best guess from government officials responsible for data collection (Gibbs et al. 2007). LPJ-GUESS simulated biomass for tree and grasses for the entire continent and as mentioned by Weber et al. (2009), Africa is a water stressed region and this would have contributed to the model's simulation of more grass biomass than tree biomass. MODIS data had percent tree cover for the continent and the classification methods may have led to areas covered by plantation or agriculture to be classified as tree and not necessarily forested regions as was meant to be presented in this study. The data and method of analysis might overestimate grass biomass based on the assumption that a decline in tree biomass would bring about an increase in grass biomass since forested areas could be converted to built-up areas or agricultural lands.

The results presented in this study on the regional total biomass and the observed changes would have been better if the study had direct field measurements of biomass and if the actual drivers of deforestation were considered as input data rather than the extrapolation of FAO change in forest area data for the period 1990 – 2000.

The FAO data on forest cover change which was an average rate of deforestation from 1990 to 2000 was extrapolated over a 30 year period based on country-specific estimates which may not be representative of the actual rate of deforestation. Additionally, countries provide deforestation rates based on best-guess estimates or use of obsolete methods of data collection.

The deforestation rate available for this study was for an entire country but in this study it was applied to each grid cell based on a country-specific basis without considering the vegetation type found in the grid cells under observation.

MODIS VCF per cent tree cover may have captured tree cover in areas that may be regenerating but are located in densely vegetated areas or captured data from agricultural fields which may have been converted to herb or grass cover, this may not be the actual representation of the tree cover at the given time the data was captured.

To accurately estimate above-ground biomass in Africa; a direct and intensive long term measurement and modelling of terrestrial carbon in the region is required which was not possible to perform in this study.

6. Conclusion and possible applications of findings

6.1. Conclusions

In this study the effect of change in forest cover on the spatial and temporal distribution of biomass in Africa was studied and the findings can be summarised as follows:

- Projecting future biomass using annual change rates is a powerful tool that could aid in the assessment of carbon flux from Africa, and how much carbon is released due to change in land use on the continent to a certain degree.

- The projected above ground biomass had an increasing trend all through the study period and southern Africa has the least in biomass (grasses and trees). This region, according to this study, may not be a major player the release of carbon to the atmosphere due to deforestation as compared with other regions.

- Most of the estimated biomass is located in the Congo basin, along the coast of West Africa and Madagascar which indicate that these regions have dense vegetation biomass and are prone to high rates of deforestation.

- This study presents an estimate of the spatial and potential distribution of carbon stocks. However, there has been no substantial evidence to suggest the role of the continent in the global carbon cycle.

- Trees store the highest amount of carbon as compared to grasses but the ability of African vegetation to sequester carbon in the future is unknown due to uncertainties such as increase in afforestation and reforestation efforts and improvement in government policies.

6.2. Possible applications of Findings

- The study will be useful in assessing the present and potential sources and sinks of carbon in Africa and it would enable the relevant stakeholders to develop mitigation strategies to abate biomass loss and climate change.
- Basis for further studies on the role of Africa in climate change mitigation and the global carbon cycle.
- Further studies on direct collection and analysis of data using improved techniques to assess and estimate above-ground biomass in Africa. Especially given that this study found a large discrepancy between the model estimates of grass biomass to literature estimates, it is suggested to re-parameterise and validate the applied simulation model LPJ-GUESS.

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Appendix A

Table A1. Country-specific annual rate of change of forest cover (%). Adapted from FAO 2003 State of the world's forest.

FOREST AREA AND AREA CHANGE							
Country/area	Land area ('000 ha)	Forest area, 2000			Forest cover change, 1990-2000		Computed rate of change
		Total forest ('000 ha)	% of land area	Area per capita (ha)	Annual change ('000 ha)	Annual rate of change (%)	Tree
Algeria	238 174	2 145	0.9	0.1	27	1.3	1.013
Angola	124 670	69 756	56	5.6	-124	-0.2	0.998
Benin	11 063	2 650	24	0.4	-70	-2.3	0.977
Botswana	56 673	12 427	21.9	7.8	-118	-0.9	0.991
Burkina Faso	27 360	7 089	25.9	0.6	-15	-0.2	0.998
Burundi	2 568	94	3.7	n.s.	-15	-9	0.91
Cameroon	46 540	23 858	51.3	1.6	-222	-0.9	0.991
Central African Rep.	62 297	22 907	36.8	6.5	-30	-0.1	0.999
Chad	125 920	12 692	10.1	1.7	-82	-0.6	0.994
Congo	34 150	22 060	64.6	7.7	-17	-0.1	0.999
Côte d'Ivoire	31 800	7 117	22.4	0.5	-265	-3.1	0.999
Dem. Rep. of the Congo	226 705	135 207	59.6	2.7	-532	-0.4	0.996
Djibouti	2 317	6	0.3	n.s.	n.s.	1(n.s.)	1
Egypt	99 545	72	0.1	n.s.	2	3.3	1.033
Equatorial Guinea	2 805	1 752	62.5	4	-11	-0.6	0.994
Eritrea	11 759	1 585	13.5	0.4	-5	-0.3	0.997
Ethiopia	110 430	4 593	4.2	0.1	-40	-0.8	0.992
Gabon	25 767	21 826	84.7	18.2	-10	1(n.s.)	1
Gambia	1 000	481	48.1	0.4	4	1	1.01
Ghana	22 754	6 335	27.8	0.3	-120	-1.7	0.983
Guinea	24 572	6 929	28.2	0.9	-35	-0.5	0.995
Guinea-Bissau	3 612	2 187	60.5	1.8	-22	-0.9	0.991
Kenya	56 915	17 096	30	0.6	-93	-0.5	0.995
Lesotho	3 035	14	0.5	n.s.	n.s.	1(n.s.)	1
Liberia	11 137	3 481	31.3	1.2	-76	-2	0.98
Libyan Arab J.	175 954	358	0.2	0.1	5	1.4	1.014
Madagascar	58 154	11 727	20.2	0.8	-117	-0.9	0.991
Malawi	9 409	2 562	27.2	0.2	-71	-2.4	0.976
Mali	122 019	13 186	10.8	1.2	-99	-0.7	0.993
Mauritania	102 522	317	0.3	0.1	-10	-2.7	0.973
Morocco	44 630	3 025	6.8	0.1	-1	1(n.s.)	1
Mozambique	78 409	30 601	39	1.6	-64	-0.2	0.998
Namibia	82 329	8 040	9.8	4.7	-73	-0.9	0.991

Niger	126 670	1 328	1	0.1	-62	-3.7	0.963
Nigeria	91 077	13 517	14.8	0.1	-398	-2.6	0.974
Rwanda	2 466	307	12.4	n.s.	-15	-3.9	0.961
Senegal	19 252	6 205	32.2	0.7	-45	-0.7	0.993
Sierra Leone	7 162	1 055	14.7	0.2	-36	-2.9	0.971
Somalia	62 734	7 515	12	0.8	-77	-1	0.99
South Africa	121 758	8 917	7.3	0.2	-8	-0.1	0.999
Sudan	237 600	61 627	25.9	2.1	-959	-1.4	0.986
Swaziland	1 721	522	30.3	0.5	6	1.2	1.012
Togo	5 439	510	9.4	0.1	-21	-3.4	0.966
Tunisia	16 362	510	3.1	0.1	1	0.2	1.002
Uganda	19 964	4 190	21	0.2	-91	-2	0.98
United Rep. of Tanzania	88 359	38 811	43.9	1.2	-91	-0.2	0.998
Western Sahara	26 600	152	0.6	0.5	n.s.	1(n.s.)	1
Zambia	74 339	31 246	42	3.5	-851	-2.4	0.976
Zimbabwe	38 685	19 040	49.2	1.7	-320	-1.5	0.985

Table A2. Showing annual biomass of trees, grass, total biomass and total biomass change (tons C/ yr^{-1}) for Africa

Year	Tree	Grass	Total Biomass	Change in Total Biomass
2001	4.32E+10	5.90E+10	1.02E+11	0.00E+00
2002	4.30E+10	5.93E+10	1.02E+11	5.42E+07
2003	4.28E+10	5.96E+10	1.02E+11	5.34E+07
2004	4.26E+10	5.99E+10	1.02E+11	5.28E+07
2005	4.23E+10	6.02E+10	1.02E+11	5.21E+07
2006	4.21E+10	6.04E+10	1.03E+11	5.14E+07
2007	4.19E+10	6.07E+10	1.03E+11	5.07E+07
2008	4.17E+10	6.10E+10	1.03E+11	5.01E+07
2009	4.15E+10	6.12E+10	1.03E+11	4.94E+07
2010	4.13E+10	6.15E+10	1.03E+11	4.88E+07
2011	4.11E+10	6.17E+10	1.03E+11	4.82E+07
2012	4.09E+10	6.20E+10	1.03E+11	4.76E+07
2013	4.07E+10	6.22E+10	1.03E+11	4.70E+07
2014	4.05E+10	6.25E+10	1.03E+11	4.65E+07
2015	4.03E+10	6.27E+10	1.03E+11	4.59E+07
2016	4.01E+10	6.29E+10	1.03E+11	4.54E+07
2017	3.99E+10	6.32E+10	1.03E+11	4.48E+07
2018	3.97E+10	6.34E+10	1.03E+11	4.43E+07
2019	3.95E+10	6.36E+10	1.03E+11	4.38E+07
2020	3.93E+10	6.39E+10	1.03E+11	4.33E+07
2021	3.91E+10	6.41E+10	1.03E+11	4.28E+07
2022	3.90E+10	6.43E+10	1.03E+11	4.23E+07
2023	3.88E+10	6.45E+10	1.03E+11	4.18E+07
2024	3.86E+10	6.48E+10	1.03E+11	4.13E+07
2025	3.84E+10	6.50E+10	1.03E+11	4.09E+07
2026	3.83E+10	6.52E+10	1.03E+11	4.05E+07

2027	3.81E+10	6.54E+10	1.03E+11	4.00E+07
2028	3.79E+10	6.56E+10	1.04E+11	3.96E+07
2029	3.78E+10	6.58E+10	1.04E+11	3.91E+07
2030	3.76E+10	6.60E+10	1.04E+11	3.87E+07

Table A3. Total biomass (TB) and change in biomass (tons C) per country

COUNTRY	2002 Total Biomass	2015 Total Biomass	2030 Total Biomass	2002 Change	2015 Change	2030 change	2002 change (%)	2015 Change (%)	2030 Change (%)
Algeria	1.09E+08	1.17E+08	1.29E+08	5.68E+05	6.72E+05	8.15E+05	0.519	0.572	0.634
Angola	3.84E+09	3.84E+09	3.84E+09	-6.78E+04	-6.69E+04	-6.53E+04	- 0.002	- 0.002	- 0.002
Benin	4.26E+08	4.31E+08	4.35E+08	4.18E+05	3.09E+05	2.18E+05	0.098	0.072	0.050
Botswana	2.00E+08	2.01E+08	2.02E+08	6.41E+04	5.70E+04	4.96E+04	0.032	0.028	0.025
Burkina Faso	2.29E+08	2.29E+08	2.29E+08	1.14E+04	1.09E+04	1.11E+04	0.005	0.005	0.005
Burundi	1.90E+08	1.90E+08	1.90E+08	-6.10E+03	-1.10E+03	-7.00E+02	- 0.003	- 0.001	- 0.000
Cameroon	5.20E+09	5.28E+09	5.37E+09	6.76E+06	6.01E+06	5.24E+06	0.130	0.114	0.098
Central African Rep.	4.17E+09	4.17E+09	4.18E+09	3.87E+05	3.83E+05	3.77E+05	0.009	0.009	0.009
Chad	3.85E+08	3.87E+08	3.90E+08	1.77E+05	1.64E+05	1.50E+05	0.046	0.042	0.038
Congo	9.06E+09	9.07E+09	9.08E+09	8.76E+05	8.60E+05	8.44E+05	0.010	0.009	0.009
Cote d'Ivory	3.50E+09	3.50E+09	3.51E+09	6.47E+05	6.39E+05	6.31E+05	0.018	0.018	0.018
Dem. Rep. of the Congo	2.91E+10	2.93E+10	2.95E+10	1.49E+07	1.41E+07	1.33E+07	0.051	0.048	0.045
Djibouti	7.59E+04	7.59E+04	7.59E+04	-1.02E-01	0.00E+00	0.00E+00	- 0.000	-	-
Egypt	3.56E+05	3.63E+05	3.75E+05	3.98E+02	6.07E+02	9.90E+02	0.112	0.167	0.264
Equatorial Guinea	3.77E+08	3.92E+08	4.08E+08	1.21E+06	1.12E+06	1.02E+06	0.321	0.285	0.250
Eritrea	1.03E+07	1.03E+07	1.03E+07	1.21E+03	1.18E+03	1.11E+03	0.012	0.011	0.011
Ethiopia	2.83E+09	2.84E+09	2.85E+09	9.02E+05	8.14E+05	7.19E+05	0.032	0.029	0.025
Gabon	6.56E+09	6.56E+09	6.56E+09	1.60E+01	0.00E+00	0.00E+00	0.000	-	-
Gambia	1.15E+07	1.13E+07	1.11E+07	-1.19E+04	-1.34E+04	-1.56E+04	- 0.103	- 0.119	- 0.140
Ghana	1.46E+09	1.49E+09	1.51E+09	2.35E+06	1.88E+06	1.45E+06	0.161	0.127	0.096
Guinea	1.01E+09	1.01E+09	1.02E+09	4.09E+05	3.82E+05	3.55E+05	0.040	0.038	0.035
Guinea-Bissau	4.19E+07	4.20E+07	4.21E+07	9.50E+03	8.40E+03	7.30E+03	0.023	0.020	0.017
Kenya	1.02E+09	1.02E+09	1.02E+09	1.99E+05	1.87E+05	1.73E+05	0.020	0.018	0.017
Lesotho	8.61E+07	8.61E+07	8.61E+07	0.00E+00	0.00E+00	0.00E+00	-	-	-
Liberia	1.50E+09	1.49E+09	1.48E+09	-1.04E+06	-8.00E+05	-5.91E+05	- 0.069	- 0.054	- 0.040
Libyan Arab J.	4.70E+06	4.81E+06	4.96E+06	7.72E+03	9.23E+03	1.14E+04	0.165	0.192	0.230
Madagascar	8.41E+09	8.45E+09	8.50E+09	3.56E+06	3.16E+06	2.76E+06	0.042	0.037	0.032
Malawi	4.15E+08	4.17E+08	4.18E+08	1.11E+05	8.09E+04	5.63E+04	0.027	0.019	0.013
Mali	3.94E+08	3.95E+08	3.97E+08	1.55E+05	1.41E+05	1.28E+05	0.039	0.036	0.032
Mauritania	2.61E+06	2.61E+06	2.61E+06	-1.56E+01	-1.18E+01	-9.46E+00	- 0.001	- 0.000	- 0.000
Morocco	7.72E+07	7.72E+07	7.72E+07	-5.68E+01	0.00E+00	0.00E+00	- 0.000	-	-
Mozambique	3.45E+09	3.45E+09	3.45E+09	1.64E+05	1.59E+05	1.55E+05	0.005	0.005	0.004
Namibia	8.38E+07	8.40E+07	8.43E+07	2.08E+04	1.84E+04	1.61E+04	0.025	0.022	0.019
Niger	2.16E+07	2.17E+07	2.18E+07	1.21E+04	7.41E+03	4.20E+03	0.056	0.034	0.019
Nigeria	3.52E+09	3.63E+09	3.73E+09	1.07E+07	7.60E+06	5.12E+06	0.304	0.209	0.137
Rwanda	2.75E+08	2.87E+08	2.96E+08	1.26E+06	7.51E+05	4.13E+05	0.458	0.261	0.140
Senegal	5.53E+07	5.57E+07	5.62E+07	3.32E+04	3.04E+04	2.73E+04	0.060	0.055	0.049
Sierra Leone	4.95E+08	5.06E+08	5.15E+08	1.07E+06	7.30E+05	4.69E+05	0.216	0.144	0.091
Somalia	1.22E+08	1.22E+08	1.22E+08	8.93E+02	6.95E+02	8.47E+02	0.001	0.001	0.001
South Africa	2.10E+09	2.10E+09	2.10E+09	-6.67E+04	-6.61E+04	-6.45E+04	- 0.003	- 0.003	- 0.003
Sudan	3.48E+09	3.52E+09	3.55E+09	3.16E+06	2.63E+06	2.13E+06	0.091	0.075	0.060
Swaziland	3.22E+07	3.18E+07	3.14E+07	-2.39E+04	-2.79E+04	-3.34E+04	- 0.074	- 0.088	- 0.107
Togo	3.13E+08	3.16E+08	3.18E+08	2.60E+05	1.65E+05	9.95E+04	0.083	0.052	0.031
Tunisia	3.27E+07	3.29E+07	3.33E+07	2.06E+04	2.10E+04	2.17E+04	0.063	0.064	0.065
Uganda	2.02E+09	2.03E+09	2.03E+09	4.40E+05	3.43E+05	2.49E+05	0.022	0.017	0.012
United Rep. of Tanzania	3.06E+09	3.06E+09	3.06E+09	2.06E+05	2.01E+05	1.95E+05	0.007	0.007	0.006
Western Sahara	1.52E+03	1.52E+03	1.52E+03	2.00E-03	0.00E+00	0.00E+00	0.000	-	-
Zambia	1.88E+09	1.93E+09	1.96E+09	3.87E+06	2.82E+06	1.96E+06	0.206	0.147	0.100
Zimbabwe	7.38E+08	7.44E+08	7.49E+08	4.73E+05	3.88E+05	3.10E+05	0.064	0.052	0.041

Table A4: Annual (sum) of tree biomass and change (tons C/yr^{-1})

YEAR	Tress Sum	Change in tree biomass
2001	4.32E+10	0.00E+00
2002	4.30E+10	-2.31E+08
2003	4.28E+10	-2.28E+08
2004	4.26E+10	-2.25E+08
2005	4.23E+10	-2.22E+08
2006	4.21E+10	-2.19E+08
2007	4.19E+10	-2.16E+08
2008	4.17E+10	-2.13E+08
2009	4.15E+10	-2.10E+08
2010	4.13E+10	-2.08E+08
2011	4.11E+10	-2.05E+08
2012	4.09E+10	-2.03E+08
2013	4.07E+10	-2.00E+08
2014	4.05E+10	-1.98E+08
2015	4.03E+10	-1.96E+08
2016	4.01E+10	-1.93E+08
2017	3.99E+10	-1.91E+08
2018	3.97E+10	-1.89E+08
2019	3.95E+10	-1.87E+08
2020	3.93E+10	-1.85E+08
2021	3.91E+10	-1.83E+08
2022	3.90E+10	-1.81E+08
2023	3.88E+10	-1.79E+08
2024	3.86E+10	-1.77E+08
2025	3.84E+10	-1.75E+08
2026	3.83E+10	-1.73E+08
2027	3.81E+10	-1.71E+08
2028	3.79E+10	-1.69E+08
2029	3.78E+10	-1.68E+08
2030	3.76E+10	-1.66E+08

Table A5: Tree biomass and changes per country (tons C)

COUNTRY	2002 Tree	2015 Tree	2030 Tree	2002 Tree Change	2015 Tree Change	2030 Tree Change
Algeria	4.95E+07	5.85E+07	7.10E+07	6.35E+05	7.51E+05	9.11E+05
Angola	1.30E+09	1.26E+09	1.23E+09	-2.60E+06	-2.53E+06	-2.46E+06
Benin	5.85E+07	4.32E+07	3.05E+07	-1.38E+06	-1.02E+06	-7.18E+05
Botswana	8.54E+06	7.60E+06	6.63E+06	-7.76E+04	-6.90E+04	-6.02E+04
Burkina Faso	1.44E+07	1.41E+07	1.36E+07	-2.89E+04	-2.82E+04	-2.74E+04
Burundi	4.10E+07	1.20E+07	2.92E+06	-4.05E+06	-1.19E+06	-2.89E+05
Cameroon	2.83E+09	2.52E+09	2.20E+09	-2.57E+07	-2.29E+07	-2.00E+07
Central African Rep.	1.69E+09	1.66E+09	1.64E+09	-1.69E+06	-1.67E+06	-1.64E+06
Chad	3.69E+07	3.41E+07	3.12E+07	-2.23E+05	-2.06E+05	-1.88E+05
Congo	5.03E+09	4.97E+09	4.89E+09	-5.03E+06	-4.97E+06	-4.90E+06
Cote d'Ivory	8.75E+08	8.63E+08	8.50E+08	-8.75E+05	-8.65E+05	-8.51E+05
Dem. Rep. of the Congo	1.76E+10	1.67E+10	1.57E+10	-7.07E+07	-6.71E+07	-6.32E+07
Djibouti	9.82E+02	9.82E+02	9.82E+02	0.00E+00	0.00E+00	0.00E+00
Egypt	2.15E+04	3.28E+04	5.33E+04	6.86E+02	1.05E+03	1.70E+03
Equatorial Guinea	2.01E+08	1.86E+08	1.70E+08	-1.21E+06	-1.12E+06	-1.03E+06
Eritrea	1.63E+05	1.57E+05	1.50E+05	-4.91E+02	-4.72E+02	-4.51E+02
Ethiopia	6.82E+08	6.14E+08	5.44E+08	-5.50E+06	-4.95E+06	-4.39E+06
Gabon	3.90E+09	3.90E+09	3.90E+09	9.83E+01	0.00E+00	0.00E+00
Gambia	7.38E+05	8.40E+05	9.76E+05	7.31E+03	8.32E+03	9.66E+03
Ghana	2.92E+08	2.34E+08	1.81E+08	-5.05E+06	-4.04E+06	-3.13E+06
Guinea	2.94E+08	2.76E+08	2.56E+08	-1.48E+06	-1.38E+06	-1.28E+06
Guinea-Bissau	1.28E+07	1.14E+07	9.94E+06	-1.16E+05	-1.03E+05	-9.03E+04
Kenya	1.17E+08	1.09E+08	1.01E+08	-5.87E+05	-5.50E+05	-5.10E+05
Lesotho	9.96E+06	9.96E+06	9.96E+06	0.00E+00	0.00E+00	0.00E+00
Liberia	8.78E+08	6.76E+08	4.99E+08	-1.79E+07	-1.38E+07	-1.02E+07
Libyan Arab J.	6.72E+05	8.06E+05	9.92E+05	9.28E+03	1.11E+04	1.37E+04
Madagascar	2.27E+09	2.02E+09	1.76E+09	-2.06E+07	-1.83E+07	-1.60E+07
Malawi	8.09E+07	5.90E+07	4.10E+07	-1.99E+06	-1.45E+06	-1.01E+06
Mali	3.22E+07	2.94E+07	2.65E+07	-2.27E+05	-2.07E+05	-1.87E+05
Mauritania	1.34E+04	9.39E+03	6.23E+03	-3.72E+02	-2.61E+02	-1.73E+02
Morocco	2.23E+07	2.23E+07	2.23E+07	2.07E+01	0.00E+00	0.00E+00
Mozambique	9.37E+08	9.13E+08	8.86E+08	-1.88E+06	-1.83E+06	-1.77E+06
Namibia	5.36E+05	4.77E+05	4.16E+05	-4.87E+03	-4.33E+03	-3.78E+03
Niger	2.10E+05	1.29E+05	7.31E+04	-8.07E+03	-4.94E+03	-2.81E+03
Nigeria	8.29E+08	5.89E+08	3.97E+08	-2.21E+07	-1.57E+07	-1.06E+07
Rwanda	4.35E+07	2.60E+07	1.43E+07	-1.77E+06	-1.05E+06	-5.80E+05
Senegal	8.09E+06	7.38E+06	6.65E+06	-5.70E+04	-5.21E+04	-4.68E+04
Sierra Leone	1.75E+08	1.19E+08	7.68E+07	-5.23E+06	-3.57E+06	-2.29E+06
Somalia	8.41E+06	7.38E+06	6.35E+06	-8.50E+04	-7.45E+04	-6.41E+04
South Africa	4.21E+08	4.16E+08	4.09E+08	-4.21E+05	-4.16E+05	-4.10E+05
Sudan	4.96E+08	4.13E+08	3.34E+08	-7.04E+06	-5.86E+06	-4.74E+06
Swaziland	5.66E+06	6.61E+06	7.90E+06	6.71E+04	7.83E+04	9.37E+04
Togo	4.37E+07	2.79E+07	1.66E+07	-1.54E+06	-9.82E+05	-5.84E+05
Tunisia	1.16E+07	1.19E+07	1.23E+07	2.32E+04	2.37E+04	2.45E+04
Uganda	5.22E+08	4.02E+08	2.97E+08	-1.07E+07	-8.20E+06	-6.05E+06
United Rep. of Tanzania	6.48E+08	6.32E+08	6.13E+08	-1.30E+06	-1.27E+06	-1.23E+06
Western Sahara	3.45E+02	3.45E+02	3.45E+02	1.00E-04	0.00E+00	0.00E+00
Zambia	4.28E+08	3.12E+08	2.17E+08	-1.05E+07	-7.68E+06	-5.34E+06
Zimbabwe	1.15E+08	9.49E+07	7.56E+07	-1.76E+06	-1.44E+06	-1.15E+06

Table A6: Annual (sum) of grass biomass and change (tons C/yr^{-1})

Year	Grass Sum	Change in Grass Biomass
2001	5.90E+10	0.00E+00
2002	5.93E+10	2.85E+08
2003	5.96E+10	2.81E+08
2004	5.99E+10	2.77E+08
2005	6.02E+10	2.74E+08
2006	6.04E+10	2.70E+08
2007	6.07E+10	2.67E+08
2008	6.10E+10	2.63E+08
2009	6.12E+10	2.60E+08
2010	6.15E+10	2.57E+08
2011	6.17E+10	2.54E+08
2012	6.20E+10	2.50E+08
2013	6.22E+10	2.47E+08
2014	6.25E+10	2.44E+08
2015	6.27E+10	2.42E+08
2016	6.29E+10	2.39E+08
2017	6.32E+10	2.36E+08
2018	6.34E+10	2.33E+08
2019	6.36E+10	2.31E+08
2020	6.39E+10	2.28E+08
2021	6.41E+10	2.25E+08
2022	6.43E+10	2.23E+08
2023	6.45E+10	2.21E+08
2024	6.48E+10	2.18E+08
2025	6.50E+10	2.16E+08
2026	6.52E+10	2.13E+08
2027	6.54E+10	2.11E+08
2028	6.56E+10	2.09E+08
2029	6.58E+10	2.07E+08
2030	6.60E+10	2.05E+08

Table A7: Grass biomass and changes per country (tons C)

COUNTRY	2002 Grass	2015 Grass	2030 Grass	2002 Grass Change	2015 Grass Change	2030 Grass Change
Algeria	5.99E+07	5.90E+07	5.77E+07	-6.68E+04	-7.90E+04	-9.59E+04
Angola	2.54E+09	2.57E+09	2.61E+09	2.53E+06	2.47E+06	2.40E+06
Benin	3.68E+08	3.88E+08	4.04E+08	1.80E+06	1.33E+06	9.36E+05
Botswana	1.91E+08	1.93E+08	1.95E+08	1.42E+05	1.26E+05	1.10E+05
Burkina Faso	2.15E+08	2.15E+08	2.16E+08	4.04E+04	3.92E+04	3.86E+04
Burundi	1.49E+08	1.78E+08	1.87E+08	4.05E+06	1.19E+06	2.88E+05
Cameroon	2.37E+09	2.77E+09	3.17E+09	3.25E+07	2.89E+07	2.52E+07
Central African Rep.	2.48E+09	2.51E+09	2.54E+09	2.08E+06	2.05E+06	2.02E+06
Chad	3.48E+08	3.53E+08	3.59E+08	4.00E+05	3.70E+05	3.38E+05
Congo	4.03E+09	4.10E+09	4.19E+09	5.91E+06	5.83E+06	5.74E+06
Cote d'Ivory	2.62E+09	2.64E+09	2.66E+09	1.52E+06	1.50E+06	1.48E+06
Dem. Rep. of the Congo	1.15E+10	1.26E+10	1.38E+10	8.56E+07	8.12E+07	7.65E+07
Djibouti	7.49E+04	7.49E+04	7.49E+04	-1.02E-01	0.00E+00	0.00E+00
Egypt	3.35E+05	3.30E+05	3.22E+05	-2.88E+02	-4.39E+02	-7.13E+02
Equatorial Guinea	1.76E+08	2.06E+08	2.38E+08	2.42E+06	2.24E+06	2.05E+06
Eritrea	1.01E+07	1.01E+07	1.02E+07	1.70E+03	1.64E+03	1.56E+03
Ethiopia	2.15E+09	2.23E+09	2.31E+09	6.40E+06	5.77E+06	5.11E+06
Gabon	2.66E+09	2.66E+09	2.66E+09	9.60E+01	0.00E+00	0.00E+00
Gambia	1.07E+07	1.05E+07	1.01E+07	-1.92E+04	-2.17E+04	-2.52E+04
Ghana	1.17E+09	1.25E+09	1.33E+09	7.40E+06	5.92E+06	4.58E+06
Guinea	7.15E+08	7.39E+08	7.65E+08	1.89E+06	1.77E+06	1.64E+06
Guinea-Bissau	2.91E+07	3.06E+07	3.22E+07	1.26E+05	1.12E+05	9.76E+04
Kenya	9.02E+08	9.12E+08	9.22E+08	7.86E+05	7.37E+05	6.83E+05
Lesotho	7.61E+07	7.61E+07	7.61E+07	0.00E+00	0.00E+00	0.00E+00
Liberia	6.26E+08	8.17E+08	9.83E+08	1.69E+07	1.30E+07	9.59E+06
Libyan Arab J.	4.02E+06	4.00E+06	3.97E+06	-1.56E+03	-1.88E+03	-2.32E+03
Madagascar	6.14E+09	6.44E+09	6.74E+09	2.42E+07	2.15E+07	1.87E+07
Malawi	3.34E+08	3.58E+08	3.77E+08	2.10E+06	1.53E+06	1.06E+06
Mali	3.61E+08	3.66E+08	3.71E+08	3.82E+05	3.48E+05	3.14E+05
Mauritania	2.60E+06	2.61E+06	2.61E+06	3.55E+02	2.49E+02	1.64E+02
Morocco	5.50E+07	5.50E+07	5.50E+07	-5.68E+01	0.00E+00	0.00E+00
Mozambique	2.51E+09	2.54E+09	2.57E+09	2.04E+06	1.99E+06	1.93E+06
Namibia	8.32E+07	8.36E+07	8.39E+07	2.57E+04	2.28E+04	1.99E+04
Niger	2.14E+07	2.16E+07	2.17E+07	2.02E+04	1.24E+04	7.01E+03
Nigeria	2.69E+09	3.05E+09	3.33E+09	3.28E+07	2.33E+07	1.57E+07
Rwanda	2.31E+08	2.61E+08	2.81E+08	3.03E+06	1.80E+06	9.94E+05
Senegal	4.72E+07	4.84E+07	4.95E+07	9.03E+04	8.24E+04	7.41E+04
Sierra Leone	3.20E+08	3.87E+08	4.38E+08	6.30E+06	4.30E+06	2.76E+06
Somalia	1.14E+08	1.15E+08	1.16E+08	8.59E+04	7.53E+04	6.49E+04
South Africa	1.68E+09	1.69E+09	1.69E+09	3.55E+05	3.51E+05	3.46E+05
Sudan	2.99E+09	3.11E+09	3.22E+09	1.02E+07	8.49E+06	6.88E+06
Swaziland	2.65E+07	2.52E+07	2.35E+07	-9.10E+04	-1.06E+05	-1.27E+05
Togo	2.70E+08	2.88E+08	3.01E+08	1.80E+06	1.15E+06	6.84E+05
Tunisia	2.11E+07	2.10E+07	2.10E+07	-2.67E+03	-2.70E+03	-2.80E+03
Uganda	1.50E+09	1.63E+09	1.74E+09	1.11E+07	8.54E+06	6.30E+06
United Rep. of Tanzania	2.41E+09	2.43E+09	2.45E+09	1.51E+06	1.47E+06	1.42E+06
Western Sahara	1.17E+03	1.17E+03	1.17E+03	2.00E-03	0.00E+00	0.00E+00
Zambia	1.46E+09	1.61E+09	1.75E+09	1.44E+07	1.05E+07	7.30E+06
Zimbabwe	6.23E+08	6.49E+08	6.74E+08	2.23E+06	1.83E+06	1.46E+06

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