A GIS based approach to investigating the potential of herbaceous bioenergy feedstocks for cellulosic bioethanol production in

Nigeria

By

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Declaration

The content of this PhD thesis is my original work and was never presented in any part of the world for any purpose. I also wish to state that there is no collaboration of any sort in this study, be it publish or not.

Abstract

Cellulosic ethanol provides a global alternative transport fuel to substitute conventional fossil fuels. The Nigerian Biofuel Policy in 2005 mandated the production and blending of gasoline with 10% bioethanol. Although, there have been indications that Nigeria has sufficient land available for 1st generation biofuel production, there is an urgent need to achieve food security for an increasing population. To these effects, this study aimed to investigate the land requirement and production potential of purposely grown herbaceous energy crops for 2nd generation cellulosic ethanol production in the six geo-political zones and states of Nigeria to meet the government Biofuel Policy.

In this study, ArcGIS software was first used to identify two target land use classes (grassland and shrubland) with the potential for cellulosic ethanol production. The two land use classes were evaluated both on a regional and state basis. The study further employed a GIS-based multi-criteria decision method to determine land suitability for four herbaceous bioenergy crop species (Alfalfa, Elephant grass, *Miscanthus x giganteus* and Switchgrass). Suitability analysis was conducted using literature-based criteria weights for temperature, rainfall, soil organic matter, soil pH, slope and elevation by zone and state.

The study further integrated Python software with ArcGIS to evaluate biomass productivity of the 4 species, where the NE zone was found to record the overall highest potential across the country, the SW was the highest in the South while SE zone generally possessed the least potential for all species. Estimates of productivity by state showed that Borno is the most potential productive state in the North and Oyo in the South. Lagos, which is largely comprised of built up areas, is the state with the least potential. In terms of crop productivity, elephant grass showed highest production potential followed by *Miscanthus x giganteus* and switchgrass while the C3 species (Alfalfa) has the least potential.

The theoretical ethanol yield based on cellulose content of each bioenergy crop showed that at a national level, elephant grass has the greatest potential of the four species at 338 billion litres production per annum, which can power 735 large-scale cellulosic ethanol processing facilities. Generally, the study demonstrated that Nigeria will require the construction of multiple process facilities in order to be able to sustainably use the potential feedstocks available.

Furthermore, the study showed that Nigeria has the potential to produce about 66 billion litres of cellulosic bioethanol per annum from the range of feedstocks evaluated. It is to this effect that the study indicated that Nigeria could potentially exceed the proposed 10% biofuel target of about 2 billion litres per annum using purposely grown herbaceous energy crops for cellulosic ethanol production.

Dedication

I dedicate this PhD thesis to my late brother who worked tirelessly to make my dream come true.

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Above all, I thank God Almighty for been the centre of this study.

Acronyms

AADL	Allied Atlantic Distilleries Ltd
AAEA	Africa Albers Equal Area Conic
AGO	Automotive Gasoline Oil
AHP	Analytical Hierarchical Process
AMN	Administrative map of Nigeria
ASCII	American Standard Code for Information Interchange
AT	Attribute Table
CBN	Central Bank of Nigeria
CF	Critical Factors
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
CH_4	Methane
DPR	Department Petroleum Resources
DEM	Digital Elevation Model
E 10	Ten Percent (10%) Ethanol Blending with 90% Gasoline
EIA	US Energy Information Administration
EU	European Union
FAO	Food and Agricultural Organisation of the United Nations
FCT	Federal Capital Territory
FDAPHS	Federal Department of Animal Production & Husbandry Services
FMARD	Federal Ministry of Agriculture and Rural Development
GDP	Gross Domestic Product
GDB	Geo-data Base
GHG	Greenhouse Gas Emission
GIS	Geographical Information System
GLCN	Global Land Cover Network
HFC	Hydrofluorocarbon
HIS	Healthcare Information Systems

IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development
IEA	International Energy Agency
IPCC	Intergovernmental Panel for Climate Change
KRPC	Kaduna Refinery and Petrochemicals
LU	Land Use
LUC	Land use change
LULC	Land Use Land Cover
MCE	Multi-Criteria Evaluation
MCDM	Multi-Criteria Decision Method
MT	Metric Tonnes
NAAS	Nigerian Annual Abstract of Statistics
NAPRI	National Animal Production Research Institutes
NBS	National Bureau of Statistics Nigeria
NC	North Central zone
NE	North East zone
NIMET	Nigerian Meteorological Agency
NNPC	Nigerian National Petroleum Cooperation
NO_2	Nitrogen Oxide
NPFS	Nigeria Programme for Food Security
NRCS	Natural Resources Conservation Service
NW	North West zone
PMS	Petrol Motor Spirit
PRPC	Port Harcourt Refinery and Petrochemical Company
PTW	Pump to wheel
PWCM	Pairwise Comparison Matrix
RFA	Renewable Fuels Association
SAW	Simple Addictive Weighting
SE	South East zone
SF_6	Sulphur Hexafluoride

SRTM	Shuttle Radar Topography Mission
SS	South South zone
SW	South West zone
TOPSIS	Technique for Order Preferences by Similarity to the Ideal Solution
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UTM	Universal Transverse Mercator
USA	United States of America
USDA	United States Department of Agriculture
WGS84	World Geodetic Survey 1984
WPM	Weighted Product Method
WRPC	Warri Refinery and Petrochemical Company
WSM	Weighted Sum Method
WTW	Well-to-Wheels
WTP	Well to Pump

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Chapter 1: Introduction

The introductory chapter forms the basic foundation and background of the study.

1.1 Background of the study

The development of environmental-friendly sources of energy has become a major concern across the globe (Stambouli and Traversa, 2002). This is due mainly to the impact of conventional fossil energy on every facet of life (Omer, 2008). The Nigerian economy is based on two major industries: agriculture and energy (Mohammed, 2016).

1.1.1 The role of agriculture within the Nigerian economy

Agriculture was in the 1960s classified as the mainstay of the Nigerian economy (Ogbalubi and Wokocha, 2013), contributing 64% to the country's Gross Domestic Product (GDP) (Izuchukwu, 2011), when Nigeria was the world's largest exporter of cocoa, palm, rubber and cotton. Following the oil boom, its share declined dramatically, and in 1988 accounted for only 8% of total GDP. By 2015 to 2016, the rate had increased from 20% to 26% of GDP following the agricultural transformation agenda imposed by the Nigerian government (AGRA, 2017). While some claimed (Ogen, 2007) that agriculture is the basis of sustainable economic growth in Nigeria, Odetola and Etumnu (2013) argued that the links and relationships between agriculture and others sectors are not strong enough to deliver the desired economic growth. This is mainly due to inadequate policies to encourage innovation in the nation's agricultural sector. Hence, the agricultural sector must be interdependent rather than competitive with other sectors to make a significant contribution to the country's economy. Currently, the Nigerian agricultural sector employs some two-thirds of the nation's work force (Izuchukwu, 2011).

Since the 1960s, Nigerian agricultural policies have been especially tailored towards achieving food security. For example, measures such as the agricultural Commodity Marketing and Pricing policy or the credit scheme were adopted to support farmers to produce more but also to enable the establishment of national commodity boards for crops like cocoa, groundnut, palm produce, cotton, rubber, and food grains and an adequate distribution of agricultural inputs such as fertilisers, agrochemicals, seeds, --+machinery and equipment (Ogbalubi and Wokocha, 2013).

About 75% of total land in Nigeria is suitable for agriculture, however, only 40% is presently under cultivatation (Omorogiuwa *et al.,* 2014). The country relies significantly on agricultural imports. For example, in 2010, Nigeria spent about US$635 billion and US$356 billion on wheat and rice imports respectively. Thus, the vast unused land area would support agricultural expansion to address food security and some primary products would be also utilized to promote biofuel development in the country (Omorogiuwa *et al.,* 2014; Agbro and Ogie 2012). Although Nigeria has high potential for bioenergy and could even become a major global player, the key element remains the identification of appropriate land suitable for bioenergy crop production (Abubakar and Abdulkarim, 2016).

1.1.2 The energy sector

Apart from agriculture, the energy sector plays a central role in national development (Kleinschmidt, 2007). Energy is a domestic necessity and a major factor which dictates the price of other goods (Amigun *et al.*, 2012). The Nigerian economy is dominated by two products, oil and gas (Galadima *et al.*, 2011). They contribute about 80% of the total value of exports (Umar and Kilishi, 2010). Although oil is key to the Nigerian economy, there are also significant environmental impacts associated with it. Effects, such as air pollution which affects both human and ecosystem health and greenhouse gas emission, are particularly obvious in the densely populated Niger Delta as a result of gas flaring from oil and gas exploration (Uyigue and Agho, 2007). There have been several other effects associated with oil and gas activities in the country since its discovery in the 1950s, such as inter-ethnic crises and fuel scarcity which had paralysed all economic activities in the country (Odularu, 2008). In addition to the environmental impacts, the diminishing rate of crude oil reserves (Igboanugo *et al.*, 2013) coupled with the desire to achieve energy security (Abila, 2012) has constituted one of the major drivers for biofuel development in Nigeria (Kumar *et al.*, 2013). According to the Nigerian Energy Commission, the country's oil reserve will deplete in time (Alamu *et al.*, 2007). Yet, Nigeria's proven crude oil reserves was almost stagnant for four years, from 2012 to 2016, with just 1.1 percent change[1]. At the end of 2016, the country's reserve accounted for 37.139 billion barrels of crude oil (ibid).

1.1.2.1. Crude oil production in Nigeria

Nigeria is the largest crude oil producer in Africa (USEIA, 2016), and the sixth and eighth largest producer and exporter of crude oil globally with a proven reserve of over 37 billion barrels (Ohimain, 2013). In 2002, total oil production was estimated at over 725 million barrels with an average daily production of 2 million barrels. Nigeria recorded a total oil production of 919 million barrels in 2005, which surpassed the 911 million produced in 2004 by 0.9% (NNPC, 2005). Table 1.1 shows the evolution of the crude oil production between 2005 and 2015. About 773 million barrels with a daily average production at 2.12 mmb/pd was reported in 2015 (NNPC, 2013, 2014 and 2015). The unstable and varied production over the years has been a major national concern and was indicated to have significant adverse effects on the country's economic growth, since oil is one of the major drivers of the nation's economy.

[1] http://vanguardngn.com/nigerias-oil-reserves-remained-almost-stagnant-four-years/, last accessed 11 September 2017.

Table 1.1: Crude oil production in Nigeria (Million barrels) (NNPC Annual Statistics, 2016)

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Quantity	919	869	803	769	780	896	866	853	800	799	774

1.1.2.2. Refining and Petrochemical Companies in Nigeria

Against the background of this production, Nigeria has three major refining and petrochemical companies which are located in Port Harcourt, Kaduna and Warri (NNPC, 2005). A fourth refinery was also constructed in Port Harcourt. The first Port Harcourt refining and petrochemical company (PRPC) was established in 1966 with an initial installed capacity of 50 thousand barrels per day (bbl/d). Subsequently in 1978, Warri Refinery (WRPC) was commissioned with an initial capacity of 125,000 bbl/d, but this was later expanded (in 1986) to 125 thousand bbl/d to increase the rate of crude oil production in Nigeria. The Kaduna refinery (KRPC) was commissioned in 1980 with an installed capacity of 100 thousand bpd. In 1986 this was also upgraded to 110 thousand bbl/d to enable refining a higher capacity of crude oil. The fourth processing facility established in Port Harcourt in 1989 to increase the rate of crude oil production. The essence of establishing such a large refining facility, with an installed capacity of 160 thousand bbl/d, was to meet the increasing demand and fulfil the dual role of supplying both the domestic and export market (Odularu, 2008). These facilities were developed to process crude oil components including gasoline (PMS) and diesel (AGO) to make Nigeria a self-sustaining country, however, they performed well below their installation capacities (NNPC, 2005). For example in 2008, the output of the Kaduna refinery was about 20%, Warri 39%, and the two Port Harcourt refineries only 18% (Table 1.2). Beside the poor refining capacity and other logistic constraints, Nigeria was unable to attain its domestic demand for petroleum products in particular because the refineries were hampered by negligence and poor maintenance (Oladepo, 2014).

Table 1.2: Capacity utilization of the Nigerian oil refineries from 1997 to 2008 (%)

Plants	Year commissioned	Installed capacity 10^3 bbl/d	2000	2001	2002	2003	2004	2005	2006	2007	2008
Kaduna Refinery & Petrochemical Co	1980	110	22.7	31.4	35	15.9	26	33.1	8.3	0.00	19.6
Port Harcourt Refinery Company	1966 (old)	50 (old)	31	60.7	52.2	41.9	31	42.2	50.3	24.9	17.8
	1989 (new) (Ogedegbe, 2016)	160 (new)	31	60.7	51.4	50.5	30.7	38.1	45.7	23.8	48.5
Warri Refinery & Petrochemical Co	1978	125	5.0	48.3	55.5	14.3	9.1	54.9	3.8	0	38.5

1.1.3 Transport fuel (Petroleum products) import in Nigeria

According to Ohimain (2013), crude oil is the major source of liquid transportation fuel in Nigeria. Based on the constraints surrounding oil production and the poor refining capacity of the four refineries to attain its domestic demand for petroleum products (Oladepo, 2014), Nigeria is currently importing the bulk of its petroleum products. In 2005, Nigeria spent US$3.6 billion to import petroleum products, mainly PMS, with no importation of AGO. (Table 1.3). In 2008, petroleum imports significantly decreased to 5.5 million MT, but again rapidly increased to 7.9 million MT in 2012. In 2015 the country imports accounted for about 7.4 million MT. Generally, the increasing rates of petroleum product imports over the years were attributed to the drop in domestic refining capacities. However, the slight increase in petroleum importation into the country from 2014 to 2015 was due largely to pipeline vandalism resulting in a loss of 181.7 MT of petroleum products valued at N21.5 billion (NNPC, 2015). Following the trends in oil production and imports in Nigeria, there has been no significant changes recorded in the sector over the last decades (Musa, 2014).

Table 1.3: Imported petroleum product in Nigeria from 2005 to 2015 (thousand metric tonnes)

Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Quantity	6.2	6.3	7.1	5.5	7.2	6.6	6.6	7.9	6.7	7.0	7.4

Source: NNPC; Annual Statistical Bulletin (2005 – 2015).

1.1.3.1 Transport fuel (PMS and AGO) import and consumption in Nigeria

Transport fuels constitute the bulk of oil consumption in Nigeria, where PMS accounts for 70% of the total petroleum product consumption in the country (Musa, 2014). In 2005, Nigeria imported 6.2 million metric tonnes (MT) of petroleum products to supplement the 9.4 million MT delivered from the domestic refineries, to meet the domestic demand. Out of the 13 billion litres of petroleum products sold in 2005, PMS accounted for over 8.6 billion litres and AGO with about 2.4 billion litres, reflecting average daily sales of 23.7 and 6.5 million litres of PMS and AGO respectively (Table 1.4). The average PMS and AGO consumption in 2008 were 23.6 and 3.9 million litres and in 2009, the average rate of AGO consumption decreased to 3.3 million litres but PMS accounted for 29 million litres per day. Petroleum products consumption in Nigeria started to decrease again from 2010 to 2012, causing unstable supply of the products.

However, it significantly increased from 2013 to 2015 to about 44 and 49 million litres of PMS and about 9 million litres of AGO on average per day. The scarcity and increased rate of petroleum products imports in Nigeria were attributed to the low operation of the domestic refineries over the past years. In addition to the low performance of the four refineries, petroleum vandals, fluctuation of crude oil prices on the international market, and the use of refined products for electricity generation have contributed to the fuel scarcity (Ohimain *et al.*, 2014). In order to address this problem related to liquid transportation fuels, the Nigerian government decided to support and promote investments into biofuel (Anyaoku, 2007). However, it was found that Nigeria consumes more PMS than AGO, hence, the basis for adopting bioethanol, which is the foundation for this study.

Table 1.4: Average daily consumption of PMS and AGO (thousand litres), Nigeria, 2005-2015

Product	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
PMS	23.7	22.8	24.3	23.6	28.5	17.4	15.6	13.7	43.5	47.7	48.7
AGO	6.5	4.5	3.8	3.9	3.3	2.4	2.7	1.9	8.8	7.8	8.9

Source: NNPC; Annual Statistical Bulletin (2005 – 2015).

1.1.4 Climate change and CO_2 emissions from the transportation sector

The rapid use of fossil fuels has immensely contributed to the increased accumulation of greenhouse gas (GHG) emissions globally in particular carbon dioxide (CO_2). This coupled with the declining rate of oil reserves (Akuru and Okoro, 2011) and over dependence of Nigeria on refined petroleum products were among the key factors that stirred the quest for research on sustainable and environmental friendly alternatives such as biofuels technology (Antizar-Ladislao and Turrion-Gomez, 2008). Climate change and resource depletion are considered as the world's largest challenges (Achike and Onoja, 2014). These are associated with the numerous effects of GHG emissions particularly from the transportation sector. The transport sector has a significant contribution to the climate change effects, such as an increased sea level, a warmer planet (Bettinger *et al.*, 2010), as well as the recently experienced tornadoes in the United States (Folger, 2011). According to Okhimamhe and Okelola (2013), the Canadian transport sector contributed 27% of the total GHG emissions in 2007 in Canada, of which 69% was from road transport. Also in USA, out of the 83.7% of the total greenhouse gas emissions (GHG) the transportation sector accounted for 33% of these emissions. In this context, the road transportation sector contributed significantly to GHG emissions, where light duty vehicles accounted for 61% of CO_2 emissions and other duty trucks 22% in 2011. The same is applicable to the EU, where between 1990 and 2011, road transportation alone contributed one-fifth of the total CO_2 emission. In the UK, fossil-based fuels in the transportation sector are responsible for 21% of GHG emissions (National Statistics, 2017). Hence, the Kyoto Protocol encourages *inter alia* to promote the development and use of renewable alternative energies to help address the adverse effects of climate change (De Chazournes, 1998) and in recent years, there has been massive pressure by governments across the world to achieve the emission targets (Leggett *et al.*, 2009).

The current economic development in Nigeria coupled with the diverse energy resources, particularly crude oil exploration (Otene *et al.*, 2016), have posed serious environmental concerns as a result of the associated GHG emissions. Adverse effects of climate change caused particularly by the transportation system have recently attracted the interests of researchers on the sustainable production and use of natural resources (Otene *et al.*, 2016). In Nigeria, CO_2 emissions increased from 68.5 million metric tonnes in 1980 to 105.2 million metric tonnes in

2005 (Okhimamhe and Okelola, 2013), and road transport was identified to be responsible for 50% of GHG emissions.

Given these statistics, Nigeria has joined the rest of the world in research regarding effective and sustainable alternative energy resources for use in the road transport sector to reduce GHG emissions (Otene *et al.* 2016; Abila 2012). In 2016, Nigeria became a signatory to the Paris Agreement on Climate Change to demonstrate the country's commitment to the global effort to reduce GHG emissions unconditionally by 20% and conditionally by 45%, which is in line with the national contribution. Although the adverse effects of GHG emissions have currently affected every region of Nigeria, they are more prone to the rich Niger Delta region which recently witnessed sea level rise and coastal erosion as a result of oil pollution accumulated for over a decade (Ehikioya, 2016). Also in 2012, flood incidences ravaged more than seven states, claiming about 400 lives, displaced 2.1 million people from their homes in addition to destroying properties and farmlands (Matawal and Maton, 2013).

Biofuels have been identified as having a clear potential to reduce the GHG emissions associated with road transport in addition to promoting the fuel security of a nation. However, to date most biofuels produced commercially are of first generation, i.e. originating from food crops. These have caused major concerns with respect to food security in many regions of the world. Considering the contribution and effects of anthropogenic GHG emission to the atmosphere (Matawal and Maton, 2013) indicated that cellulosic biofuels technology could replace fossil fuels in order to reduce CO_2 emissions by 50% if sustainably produced. It is to this end that Aderogba (2011) recommended for research to focus on the causes, sources, effects and addressing the environmental impacts of GHG emissions (Aderogba, 2013). Bioenergy crops with low life-cycle emissions have a clear role to play in combating GHG emission reduction. These feedstocks, if sustainably produced and utilized, would avoid possible competition with land use and food security (Allwood *et al.*, 2014).

Most countries have adopted renewable energy systems as a measure to tackle these problems due to its minimum pollution contribution as well as several other environmental benefits (Mohammed *et al.*, 2012). The increasing concerns of political instability in the major oil producing regions of the world and climate change could have significant implications to energy supply if adequate measures are not taken (Höök and Tang, 2013; Tang *et al.*, 2015). Hence, the call for research in alternative renewable energy sources (Alamu *et al.*, 2007) of which biomass has being adopted as one of the best alternative renewable resources to ensure energy security (Goldemberg, 2007). Biofuels are the preferred choice to substitute refined petroleum in order to reduce the emissions of greenhouse gases (Fiorese and Guariso, 2010). They can provide high-energy output to supplement rapidly depleting fossil fuel reserves (Agbro and Ogie, 2012). Though, biofuels alone may not be a complete replacement to current energy consumption, they can contribute to the expansion of global energy resources (Timmons *et al.*, 2016).

Chapter 2: Literature Review

This chapter provides an integral part of the study looking at first and second generation bioethanol production and the policies that have been used in various countries/regions to promote biofuel development.

2.1 What are biofuels?

Biofuels are classified as solid, liquid and gaseous fuels produced from renewable biomass feedstocks. Though this study is limited to bioethanol there are other kinds of liquid biofuels such as biodiesel, methanol, Fischer-Tropsch liquids fuels, and gaseous fuels such as biogas, bio-hydrogen and bio-methane (Demirbas, 2008). Of these, bioethanol and biodiesel are the primary biofuels based on their scale of production (Jegannathan *et al.*, 2009). Bioethanol is predominantly produced from plant biomass and has been widely adopted as an alternative source to mitigate the effects of global warming (Davis *et al.*, 2009). Bioethanol can also be defined as an ethanol fuel produced from a range of organic plants (biomass) as well as the biodegradable fraction of municipal solid waste (Antizar-Ladislao and Turrion-Gomez, 2008). Similarly, biodiesel is a liquid fuel derived from the esterification of vegetable oils and animal fats (Jegannathan *et al.*, 2009). Bioethanol is the focus of this study because gasoline (PMS) accounts for about 70% of road transport fuel consumption in Nigeria.

2.1.1 First generation bioethanol

First generation bioethanol is refined from sugar/starch rich crops. As indicated by Ohimain (2015), first generation bioethanol uses edible food crops as the chief feedstock for production (Table 2.1).

Table 2.1: Classification of biofuels based on feedstock type and conversion technologies

Generation	Feedstock type	Feedstock	Fuel type	Conversion technology
First	Food crops	Sugarcane	Bioethanol	Microbial sugar fermentation
		Sweet sorghum	Bioethanol	
		Cassava	Bioethanol	Starch hydrolysis and microbial
		Potatoes	Bioethanol	sugar fermentation
		Yam	Bioethanol	
		Maize	Bioethanol	
		Soybean	Biodiesel	Extraction and esterification
Second	Non-food crops/waste/energy crops	Wood	Bioethanol	Thermochemical conversion
		Straw	Biomethanol	(pyrolysis and gasification)
		Grasses	Biochemicals	Fischer-Tropsch synthesis
		Peelings	Bioethanol	
		Solid waste	Biogas	Anaerobic digestion
		Sunflower	Biodiesel	(biogasification
		Jatropha	Biodiesel	Extraction and esterification
Third		Algae	Microalgae	Extraction and esterification
			Macroalgae	pyrolysis, gasification, hydrothermal
				and fermentation

According to Khattak *et al.*, (2016) bioethanol has been in existence for over 80 years. Henry Ford built the first bioethanol plant in USA in 1937 (Kovarik, 2013). The plant produced anhydrous bioethanol at 10% blend, but later closed down due to bankruptcy in 1939. Further interest was renewed in 1970s after the oil embargo. This was as a result of the rise in oil prices which considered biofuels to be more cost effective than petroleum products (Naik *et al.*, 2010). Bioethanol production has recorded tremendous increase across the world since 2000 (Fig 2.1). From 1975 to 2005, the global bioethanol production increased from 17.3 billion litres to 44.8 billion litres, of which United States accounted for 44%, Brazil 41% and the EU 13% (Heinimö and Junginger, 2009). Later in 2010, production increased to 85.6 billion litres, of which Brazil accounted for approximately 28 billion litres (Goldemberg, 2013).

In 2012 first generation bioethanol grew to over 110 billion litres. In contrast, biodiesel production grew from 4 billion litres in 2005 to 18 billion litres in 2010 and 30 billion litres in 2014 (UNCTAD, 2016). Significant growth has been achieved in the global biofuel market over the past decade and is expected to contribute up to 7% of the global transport fuels in 2030 (Escobar *et al.*, 2009). However, despite the importance of first generation biofuels and their potential for reducing CO_2 and providing domestic energy security, there are growing concerns regarding their impacts on food prices, environmental and carbon balances (Wright, 2013).

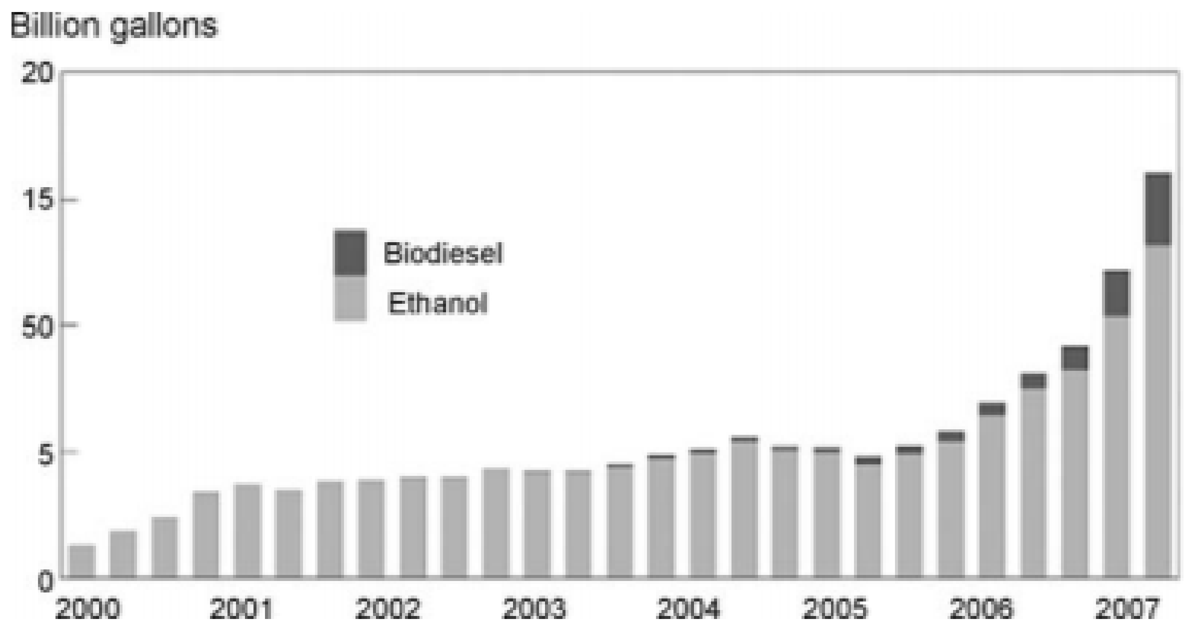

Figure 2.1: Global Production of bioethanol and biodiesel (Jegannathan *et al.*, 2009).

2.1.2 Second generation bioethanol production

The criticism and concerns over the sustainability of many first-generation biofuels like, for example, the 'food-versus-fuel' conflict, have led the nations to seek potential alternative feedstocks otherwise known as second-generation biofuels (Naik *et al.*, 2010).

In 2013, what was once considered as a theoretical policy debate became a reality as cellulosic and waste-based fuels commenced production on a commercial scale (UNCTAD, 2016). This occurred when INEOS Bio (a leading producer of biodiesel) completed the construction of its cellulosic ethanol plant in Florida. Second generation cellulosic ethanol production has the potential to employ a range of non-edible feedstock sources mainly from plant biomass, such as forestry waste (including brash, bark, saw dust and wood chippings), and agricultural wastes (including sugar cane bagasse, corn stover and rice straw), as well as purposely grown energy crops, such as miscanthus and switchgrass. The use of this wide range of feedstocks helps to address the food versus fuel conflict, while also minimising competition for land and environmental impacts associated with first generation biofuel technology (Dias *et al.,* 2012). Second generation biofuel markets have been predicted to achieve 50% growth between 2014 and 2020, with a value of US$ 24 billion by 2020. Global cellulosic biofuel demand in the road transportation sector has also been anticipated to increase from 123 billion litres in 2013 to over 193 billion litres by 2022 (UNCTAD, 2016).

2.1.3 Greenhouse gas emissions of first and second generation bioethanol relative to gasoline

The significant contribution of global greenhouse gas emissions by the transportation sector has increased motivation for the promotion of biofuels.

Bioethanol has the potential to significantly decrease the environmental impacts caused by conventional fuels (Dias *et al.*, 2012). It was indicated that first generation biofuels must reduce life-cycle emissions by 50% and advanced cellulosic biofuel by 60% to be qualified as sustainable alternative sources of energy to replace fossil fuels (UNCTAD, 2016). These sustainability criteria were introduced in the European Union as part of the EU Renewable Energy Directive (RED) of December 2012 and in the US via the Renewable Fuel Standard

(RFS) endorsed under the Energy Policy Act of 2005 and expanded under the Energy Independence and Security Act of 2007.

There have been interesting reports of the life-cycle GHG emissions mitigation potential for cellulosic biofuels of 60 to 120% (IEA, 2010). To this end Wang *et al.* (2012) compared the GHG emissions of bioethanol from corn, sugarcane, corn stover, switchgrass and miscanthus to gasoline. The study showed that bioethanol from these respective feedstocks has the capability to reduce life-cycle GHG emissions by 19 to 48%, 40 to 62%, 90 to 103%, 77 to 97% and 101 to 115% respectively for the different feedstocks. It was also identified that the life-cycle GHG emissions of bioethanol from corn and sugarcane were greater than the cellulosic bioethanol from corn stover, switchgrass and miscanthus species. These therefore showed that second generation bioethanol has a positive impact on CO_2 emissions (IEA, 2010).

The well-to-wheels (WTW) GHG emissions of the six energy pathways (i.e. gasoline, corn, sugarcane, corn stover, switchgrass and miscanthus) are shown Figure 2.3. The WTW GHG emissions were separated to include well to pump (WTP), pump to wheel (PTW), land use change (LUC) GHG emissions and the biogenic CO_2, (i.e. carbon in bioethanol). Combustion emissions (PTW) were reported to be the most significant source of GHG emission for all the six fuel pathways.

In considering the GHG emission contribution from land use change of the five bioethanol pathways, corn and sugarcane -based bioethanol were reported to have significant well or field-to-pump GHG emissions compared to the three cellulosic bioethanol pathways produced from corn stover, switchgrass and miscanthus species. Significant negative LUC GHG emissions were also identified from bioethanol produced from miscanthus species. The negative land use change emission was as a result of the increased soil organic carbon content generated during the growing of the perennial crop species. This therefore indicated that cellulosic bioethanol has significant potential for reductions in GHG emissions from the transport sector.

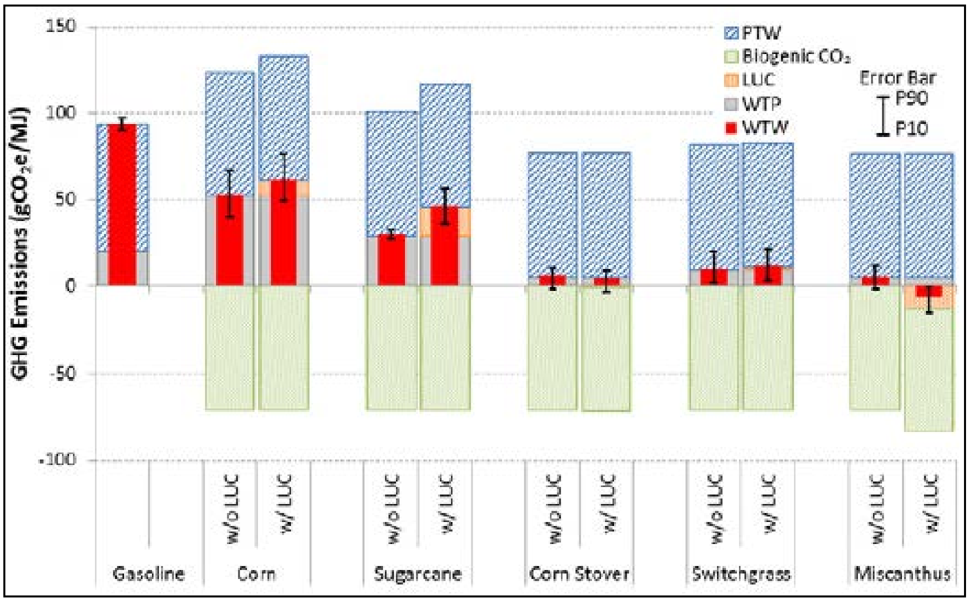

Figure 2.2: Well-to-wheel greenhouse gas emissions (CO_2) for six conventional and renewable energy pathways comprising of gasoline, corn, sugarcane, corn stover, switchgrass and miscanthus (Wang *et al.*, 2012).

The contribution of WTW GHG emissions for the six conventional and renewable pathways is shown in Figure 2.3. An average life-cycle GHG emissions of 94 g CO_2e M/J was reported for gasoline, whereas about 79% of WTW GHG emissions comes from the combustion. The petroleum refining processes contributes 12% of the emissions, while the transportation and recovery activities contribute 9% of emissions (Fig 2. 3a).

Conventional bioethanol from corn contributes average life-cycle GHG emissions of 76g CO_2e M/J, of which fuel processing accounts for 41% of the total GHG emissions, 36% of the emissions comes from agricultural production of the feedstock largely attributed to fertilizer production and use. Land use change emission from corn farming accounts for 12%, while transportation and fossil energy use accounts for a small amount of the total GHG emission (Fig 2.3b). Bioethanol from sugarcane contributes average life-cycle GHG emissions of 45g CO_2e M/J, where LUC accounts for 36% of total GHG emissions. Transport activities of sugarcane bioethanol accounts for 24% of total GHG emissions (Fig 2.3c). The average life-cycle GHG emissions of bioethanol from corn stover and switchgrass were reported to contribute only 23 and 29g CO_2e M/J compared to 1st generation ethanol fuels (Fig 2.3d and e). Also, bioethanol from miscanthus was reported to have an average life-cycle GHG emissions of 22g CO_2e M/J (Fig 2.3f). It was further indicated that the technological advancements in cellulosic bioethanol production could improve the life- cycle assessment of future biofuel production. Such advancement would enable integration of Combined Heat and Power equipment in the cellulosic processing facilities to generate electricity to power the biofuel process (Wang *et al.,* 2012) with the potential to also produce high value additional products in the so called bio-refinery concept.

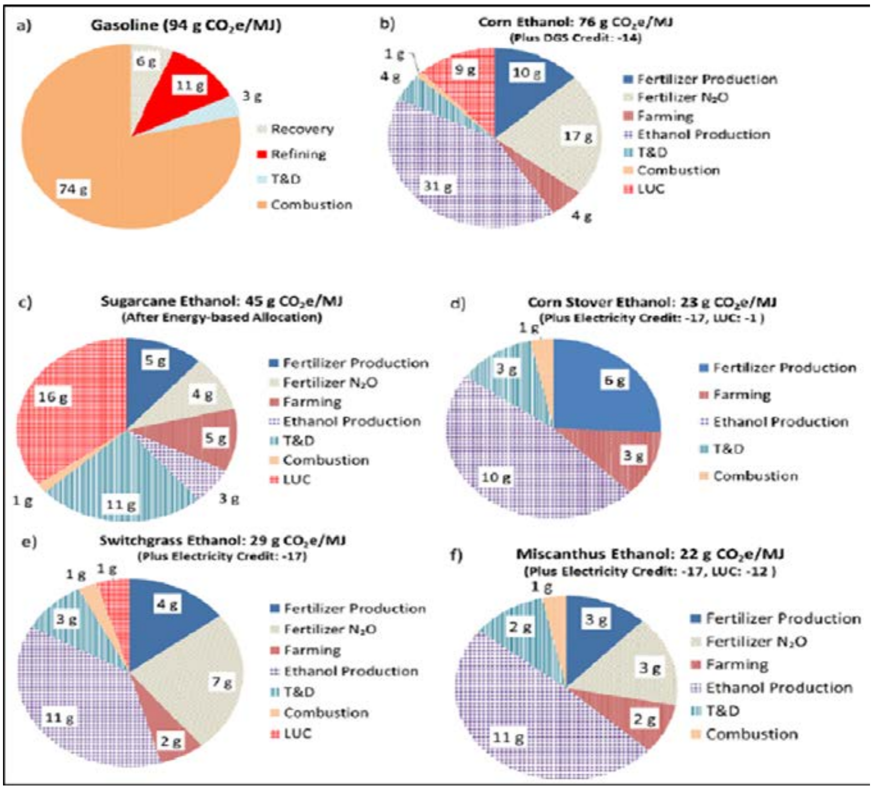

Figure 2.3: Share of GHG emissions by a) gasoline, and bioethanol produced from a range of feedstocks i.e. b) corn , c) sugarcane , d) corn stover, e) switchgrass and f) miscanthus (Wang *et al.*, 2012).

2.2 Drivers for biofuels

Biofuels have gained considerable attention from governments across the globe due to their proficiency to replace fossil-based fuels coupled with the capability to address issues surrounding climate change. One of the key drivers of biofuels are their environmental benefits such as enhanced biodiversity (Taylor, 2008). Moreover, it is argued that biofuel technology could contribute to the general development of rural economies, by providing sustainable jobs, business opportunities and environmental protection both in the developed and developing world.

The use of indigenous renewable energy resources could provide the potential for zero or almost zero emissions, reduced oil dependence as well as economic revitalization by increasing the demand and prices of agricultural products (Demirbas, 2009). Changes in governmental energy policies worldwide also constitute key drivers for the promotion of renewable liquid transportation fuels, such as ethanol fuels, and these policies are being influenced mostly by the limited availability of conventional fossil fuels (Speirs *et al.,* 2015).

The diminishing rate of fossil fuel reserves (Shafiee and Topal, 2009) and price volatility of refined petroleum products have further increased the global interest for research on alternative energy sources (Shafiee and Topal, 2010). For example, the US government offers biofuel subsidies (for blending bioethanol with gasoline) and tax preferences worth millions of dollars to encourage companies to expand bioethanol production and use. POET-DSM and Dupont (two big players in the cellulosic ethanol industry) have built processing facilities in Idaho as well as Abengoa in Kansas, that use waste corn materials such as cobs, leaf and husk to produce cellulosic ethanol (Zhang, 2016). However, Brazil was the first country to build a bioethanol-based economy and for a long time was the global leader in bioethanol production. In the Brazilian context, bioethanol was found to be economically attractive due to its contribution to the country's economic growth (Soccol *et al.*, 2010) based on development of the existing sugar industry.

2.3 Biofuel Policy in Brazil

According to Tyner (2008) ethanol production has long been in existence in Brazil and it was built around the sugar industry with sugarcane as the main feedstock. The oil price shocks of the 1970s, which resulted in high payments for oil imports (80% of its petroleum was imported), was one of the drivers that pushed bioethanol production in Brazil.

According to Balat and Balat (2009), the history of ethanol production dates back to 1975 when Brazil initiated and established the National Alcohol Fuel Programme, otherwise known as the

‘*ProAlcool Programme’* that helped revitalize the ethanol industry (Hira and De Oliveira, 2009).

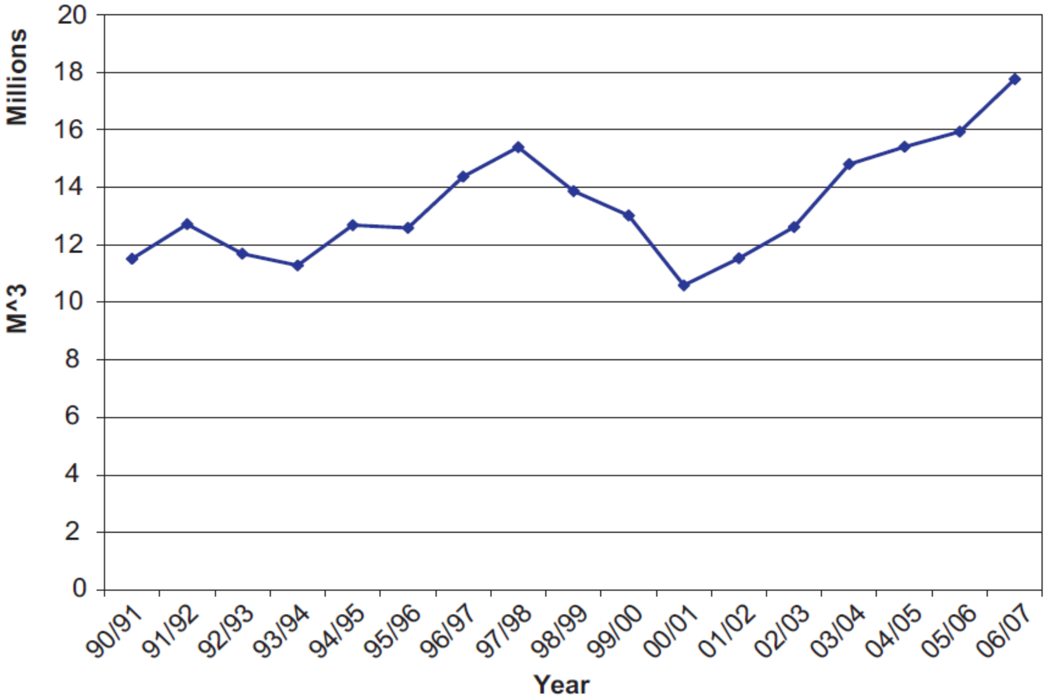

Figure 2.4: Brazil total alcohol production, 1990-2007 (Hira and De Oliveira, 2009).

The essence of the ProAlcool Programme was to achieve a sustainable energy future using sugarcane as a renewable energy feedstock. The programme also enabled the substitution of foreign imported oil with sugarcane-based ethanol (Rosillo-Calle and Cortez, 1998). In order to achieve the aim of this programme, the government of Brazil provided tax breaks to encourage farmers to produce abundant feedstocks that would enable the country to achieve the production of 30 billion litres per annum (Ohimain, 2013). The government also created an institutional framework, involving ministries and inter-ministerial commissions, which was responsible with the evaluation and financing of projects related to the production of bioethanol.

Moreover, the Brazilian government, via these institutions, proposed to install annexed distilleries within the existing plants and enable the production of sugarcane-based ethanol.

The Brazilian ethanol industry has contributed significantly to the political stability and the economic growth of the country as a whole, saving about US$28.7 billion of 220,000 barrels/day of imported petroleum products (Rosillo-Calle and Cortez, 1998). Currently, the Brazilian bioethanol industry contributes 2.3% to the Brazilian GDP and supports 4.5 million jobs (Basso *et al.*, 2011). Brazil is the largest exporter and the second largest producer of bioethanol in the world after the United States (Basso *et al.*, 2011).

According to Nass *et al.* (2007) government policies and incentives, such as low interest loans, were necessary for the successful establishment of the bioethanol industry in Brazil. Government policies to reduce the price of sugar and construction of low producing sugar facilities were also provided (Cordonnier, 2008). Among other incentives received by the ethanol sector, the Brazilian government invested heavily in research and development to ensure rapid increased ethanol production. To avoid possible competition between sugarcane for ethanol and sugar production, the government imposed export controls to regulate the production and supply of the raw material. The essence of this measure was to grant confidence and assurance to growers (Nass *et al.*, 2007). There is little doubt that Brazil has become one of the largest bioethanol producers due to its heavy subsidies and incentives (Wright, 2006). The policies mandated a blending target of at least 22% ethanol as well as the use of hydrous bioethanol (96% ethanol) to replace gasoline. Based on this development, the government provided tax incentives to encourage the automobile industries to produce flexi-fuel vehicles, and currently Brazil has over 80% flexible-fuel capability (Mojarro, 2014). These are strong indications that the success story of the Brazilian bioethanol production was made possible by its government support and it serves as a lesson for other countries to follow (Goldemberg, 2013). However, according to Hira and De Oliveira (2009) it was obvious from the lessons of Brazil that the removal of subsidies and regulations in 1990s as well as other government support, such as the ProAlcool Programme that was abolished in 1991, was very detrimental to the growth of the Brazilian ethanol industry. This implies that there is need for government support in its infant industry phase and during potential market crises.

2.4 Biofuel Policies in the United States

The United States has promoted biofuels since 1978 with a variety of policies and subsidies to become currently the global leader in bioethanol production. The substantial growth recorded in the industry was initiated by a government subsidy provided through the Energy Policy Act of 1978 (Tyner, 2015). In 2001, ethanol production significantly grew to over 1.7 billion gallons (Shapouri *et al.*, 2002). Moreover, according to a new Energy Policy Act of 2005, energy security issues in the US was one of the major drivers that contributed to the demand for cellulosic ethanol production (Lavigne and Powers, 2007). This new Energy Policy Act echoed the need to diversify the energy sources to be able to produce large-scale alternative renewable sources that can substitute for petroleum-based fuels. This therefore required new technologies such as cellulosic technology to meet the world's energy demand (Farrell *et al,* 2006). The Energy Policy Act of 2005 established a Renewable Fuel Standard (RFS) which mandated specific targets for renewable fuel use based on type of feedstock and their GHG intensity relative to fossil fuels. The current RFS called for 57 billion litres (15 billion gallons) of first generation biofuel (mainly corn based ethanol) by 2015 and 60.5 litres (22 billion gallons) of cellulosic ethanol by 2022.

In general, the energy policy perspective places much emphasis on bioethanol production to increase the chances of achieving energy security and reduce the dependence on foreign crude oil imports (Lavigne and Powers, 2007). In 2008, the US overtook Brazil as the world leader in ethanol production, contributing over half of the global bioethanol production (Lamers *et al.*, 2011).

2.5 EU Biofuels Policies

The European Parliament and the European Council adopted a directive (Directive 2003/30/EC) to promote the use of biofuels for transport in order to reduce fossil fuel use and CO_2 emissions. This directive required all member states to replace 2% of their diesel and petrol with biofuels (although deviations were possible when justified) by 2005, plus a further target of 5.75% by 2010. In addition, the Renewable Energy Directive (Directive 2009/28/EC) established in 2009 set up a minimum target for each member state of 10% by 2020. To count towards the EU target of 10%, biofuels must meet certain sustainability criteria, e.g. a net GHG saving of 35% compared to fossil fuels, which should increase to 50% by 2017 and at least 60% for new installations. Net carbon emissions from indirect land use change were not included. In September 2013 the EU also proposed a cap on the contribution of first generation biofuels from crops to 6% of this 10% target. This means that second generation biofuel production will have to come on stream in the EU to meet the 2020 deadline. However, this is subject to ratification from each member state but there is concern that this may provide some uncertainty for the biofuels industry as the target was scaled down from 10% to 6%.

In line with the EU's Renewable Energy Directive, the UK was required to implement 15% of its primary energy from renewables as well as 10% of biofuels to its transport fuels by 2020 (Byles *et al.*, 2012).

Based on these targets and commitments, biofuels have been widely accepted as an alternative to fossil fuel energies, which could contribute significantly to the reduction of CO_2 emissions in the transport sector, if sustainably managed (Hammond *et al.*, 2008).

2.6 Nigerian Biofuel Policy and Initiatives

Nigerian biofuel production is currently at an early stage of development. Hence necessary policies, regulatory frameworks as well as incentives are needed to help develop the industry in line with what has happened in Brazil, the USA and the EU. In recent years, biofuels have become very popular due to the country's quest for more sustainable, cheaper and environmental friendly alternative fuels to provide for an ever increasing population. Hence, several stakeholders, such as the Nigerian National Petroleum Corporation (NNPC), private investors and farmers as well as research institutes have been actively involved in the so called "Nigerian Biofuel Project" (Galadima *et al.*, 2011; Ohimain, 2013). The Nigerian Biofuel Policy and Incentives were drafted and approved by the Federal Government of Nigeria in 2007 and aimed to link the agricultural sector with the energy industries, with the sole intention of stimulating development in the Nigerian agricultural sector. In order to achieve this aim, the government created a department known as the Nigerian National Petroleum Corporation Renewable Energy Development (NNPCRED). Moreover, in order to ensure policy implementation, the government established the Biofuel Energy Commission (Oniemola & Sanusi, 2009).

As stated in the Official Gazette of the country's Biofuel Policy and Incentives, the NNPC was mandated to create an environment for the take-off of a viable domestic biofuel industry. The essence of this mandate was to gradually reduce Nigeria's over dependence on imported petroleum products, reduce the environmental impacts of oil and gas exploration and create sustainable jobs in the country (Galadima *et al.,* 2011).

The programme aimed to integrate the agricultural sector with the downstream oil and gas sector and it was anticipated to make significant impact on petroleum products quality enhancement (Anyaoku, 2007), control the increasing problems of unemployment and the high rate of poverty in Nigeria (Abila, 2012). It was on this note that the government introduced biofuels development to help mitigate these problems (Galadima *et al.*, 2011). Furthermore, this policy allows for NNPC to blend gasoline and diesel with 10% bioethanol and 20% biodiesel known as the " E10 and B20 blends" (Ohimain, 2013). This programme was meant to be achieved by seeding the market, firstly with crude ethanol imported from Brazil while the second phase would promote the implementation of domestic biofuel production in Nigeria (Abila, 2012). Nigeria, like Brazil, has proposed to employ a supply-led approach with policies that are market-driven. Hence, the country will not only depend on Brazil for information but signed a memorandum of understanding with the Brazilian government in 2005 to seed the ethanol market (Akande and Olorunfemi, 2009).

The federal government of Nigeria through its biofuel policy provided a 10 year target to achieve the E10 blending requirement of gasoline with bioethanol. According to Abila (2012), the government played a major role in providing the needed support and foundation for the development of a biofuel sector. One of the remarkable policies for incentivising the take-off and development of the project in Nigeria is the economic and financial framework. This notable government support include provision of income tax relief for a period of 10 years, import and custom duty waivers for bioethanol imports to meet the E10 blending targets and imports of machinery as well as other essential materials for the establishment of a feedstock industry. The government also provided preferential long term loans to investors who qualified for the pioneer status (Abila, 2012) and based on the regulatory framework, the Department of Petroleum Resources (DPR) under the Petroleum Act enabled the sale and consumption of ethanol blended fuels required for all automotive use across the country. Overall, the Nigerian government set aside about N10 billion for biofuel investors as preferential loans to complement the existing N50 billion meant for the construction of biofuel processing facilities. The government would also grant an initial 10-year waiver to the pioneer status holders with the possibility of extending the grant to an additional 5 years. To this effect, incentives such as tax reductions would also be granted to all businesses related to the production and supply of agricultural-based biofuel feedstocks.

In terms of the industry classification, the policy would guide and treat all investments in the biofuel industry as agro-allied based activities. Under the industry structure, the National Biofuel Policy would support producers and growers thereby providing cohesion to enable integration of the biofuel feedstock plantations and processing facilities. Also, the government would encourage biofuel operators with adequate resources to support the operations of growers. The Biofuels Energy Commission was charged with the sole responsibility of reviewing and assessing the economic, environmental and social impact of biofuel activities periodically and to also consider necessary policies changes required. The Biofuel Policy implementation further recommended the establishment and support for a Biofuels Research Agency. This agency was to monitor intra-industry commerce, mainly between the growers and biofuel producers to disseminate information to investors and other interested members of the public. Thus, they liaise with other government agencies and ministries as well as research institutes, such as the National Cereals Research Institute, National Root Crops Research Institute, International Institute of Tropical Agriculture and other relevant bodies like the Institute for Agricultural Research and Extension Services, the Agricultural Research Council of Nigeria and the National Biotechnology Development Agency. These organizations are therefore mandated with the responsibility of developing biofuel feedstocks in Nigeria. The Biofuel Research Agency acts as the central body for coordinating all biofuel research activities in Nigeria.

In order to encourage synergy in both the private and public sectors, the Federal Government was to contribute 100% of its resources to support research related to feedstock production and improved farming practices. Additionally, about 0.25% of the total revenue generated by the biofuel industry would be used to support such studies. It is also interesting to note that the oil and gas sector through the Petroleum Technology Development Fund was required to contribute towards biofuel research and development. To further ensure the policy implementations, all expenditures on research and development in the biofuel industry are fully tax deductible.

The Nigerian Biofuel Policy made considerable provision to exempt the industry from every form of import and custom duties and other forms of taxes charges. These exemptions were to ensure adequate supply of biofuels to the domestic market as related to the importation of petroleum products. It was further indicated that the tax exemption on biofuel companies would have an initial period of 10 years after which it could be renewed based on the prevailing circumstances. All contracts and sub-contractors related to the biofuel industries would also be exempted from import duties, taxes and levies as well as charges of a similar nature for importing the necessary equipment e.g., machinery, chemicals, fertilizers, pesticides and other materials for the construction of processing plants as well as tractors, harvesters, haulers irrigation equipment for the purpose of carrying out mechanised agricultural production.

As a consequence, there were several anticipated benefits of the policy which included the diversification of the country's sources of revenue, sustainable job creation and rural empowerment while improving agricultural benefits by promoting agricultural research, to ensure a sustainable provision of energy in Nigeria. This helps to reduce the environmental pollution associated with oil and gas activities and tailpipe emissions (Galadinma *et al.*, 2011). Apart from the primary purpose of substituting gasoline with bioethanol, ethanol can as well be used as octane enhancers to replace lead and other toxic gasoline additives (Galadinma *et al.*, 2011).

There have been some conflicts, gaps and inconsistencies currently identified in the Nigerian Biofuel Policy and Incentives. Like Brazil, the Nigerian government needed to formulate policies that have legislative support and adopt a new legal framework to complement traditional biofuel feedstocks. However, since the inception of the policy, the Nigerian government has not encouraged the research and development required to enable successful and sustainable development of the biofuel industry, as was the case in Brazil. Furthermore, there has been little or no effort for biofuel manpower development in the country through robust and sound institutional procedures to facilitate and finance such projects (Oniemola & Sanusi, 2009). The most interesting conflict was where the policy inadvertently proposed to use major national staple foods as feedstocks for biofuel production without considering the potential food versus fuel conflicts that could arise (Ohimain, 2013). The policy referred to first generation bioethanol feedstocks, such as cassava, sweat potato and maize, as cellulosic feedstocks (second generation) while typically, cellulosic feedstocks are obtained from agricultural residues, energy crops, such as switchgrass and wood wastes. Furthermore, the policy considered the development of transgenic varieties of cassava, sugarcane, sweet potato, and maize without considering the environmental and agronomic impacts of these (transgenic) crops to the native species.

Though the National Biofuel Policy indicated that agricultural land will be used for biofuel development it did not consider the food security situation in the country. Although biofuel production in Nigeria is a worthwhile venture it may not necessarily succeed if the government fails to address key areas of concern such as food security (Oshewolo, 2012).

This follows serious concerns towards the impact of biofuel production on increasing the cost of food across the world of which Nigeria is not left out. Currently the country is facing food shortages and is struggling to achieve food security for its growing population. The only way Nigeria can successfully and sustainably achieve its biofuel production target is to embark on extensive research on the aforementioned purposely grown energy crops to help address this problem and achieve food security by increasing the country's cropland (Ohimain, 2013) as well as energy security by maximizing the utilisation of other areas like grassland and shrubland.

2.7 Biofuel production in Nigeria

The federal government of Nigeria, through its National Biofuel Policy planned to use various first generation feedstocks, such as cassava, sugarcane and sorghum, for bioethanol production (Table 2.1). Based on the biofuel policy, the government commited US$3.9 billion for the construction of 19 processing plants, which were designed to enable the production of over 2.7 billion litres of biofuels (Agboola and Agboola, 2011). Out of the 20 pioneer projects, ten bio-refineries were designed to use cassava, eight to use sugarcane and the remaining two to the usage of sorghum (Ohimain *et al.*, 2014). However as at 2015 (Table 2.2), out of the total number of projects, four are at the conception phase, seven under construction, eight at the planning phase and only one is currently in operation. The four biofuel projects still in the conception phase were designed to use edible food, particularly cassava, as the main feedstocks for bioethanol production. Cassava is produced in almost all of the 36 states of Nigeria purposely for human consumption and it remains an integral product for attaining food security in Nigeria. The leaves are used as vegetable for both human and livestock consumption, the stem for plant propagation and the roots are mainly processed into food products.

For example, cassava flour popularly known as '*garri*' in Africa is used all over the continent for human consumption. If cassava-based ethanol is blended with gasoline using a ratio of 9:1 than this can be described as an 'E10 blend'. Therefore based on the 2010 domestic PMS consumption at 12.775 x 10^9 litres, about 12.8 million tonnes of cassava would be required to produce 1.2775 x 10^9 litres of bioethanol. This amount of cassava if used for bioethanol production would put the country in clear danger of food insecurity (Agboola and Agboola, 2011), if considering the country's 2013 production at 54 million tonnes (Olaniyan, 2015).

In terms of bioethanol production, the Nigerian biofuel industry is still in its early stage. All four NNPC pioneer projects, which were designed to use about 3 to 4 million tonnes of raw cassava as the main feedstocks, are still in the construction stage. Also, Global Biofuels Ltd, a national company, which is designed to use sorghum, is currently constructing two ethanol refineries, one in Ondo state and the other in Ekiti state.

Apart from the Savannah Sugar Company, which is currently the only functional sugar industry in Nigeria, and which is planning to expand its production by incorporating 100 million litres of bioethanol (Ohimain, 2015), Allied Atlantic Distilleries Limited (AADL) is the only Nigerian biofuel plant in operation. The company, which has an initial installation capacity of 10 million litres per year (Table 2.3 and Table 2.4), was commissioned in 2002 and started commercial production in 2012. The company is currently using cassava as the main feedstock to produce 9 million litres of bioethanol annually and is expected to increase production to 22 million litres before 2025 (Graffham *et al.*, 2013; Olawale, 2014). However, since production is very low, at 9 million litres per annum, and is not in line with the national biofuel target due to insufficient supply of the feedstock, Nigeria now requires other abundant alternative feedstocks. These include agricultural feedstocks and purposely grown energy crops to meet with the biofuel target.

Table 2.2: Pioneer bioethanol projects in Nigeria (Ohimain, 2015).

Pioneers	Projects	Feedstocks	Project summary, ethanol production/year
NNPC	Automotive biofuels project (Kwali sugarcane ethanol project) Automotive biofuels project Automotive biofuels project	Sugarcane Sugarcane Cassava	120 million litres 10-15 MW (electricity) 75 million litres, 116,810 metric tonnes (sugar) 40-60 million litres
Global Biofuels Ltd	Ethanol refinery and sorghum firm	Sweet sorghum	84 million litres, biorefinery + farm (estimated)
Ethanig (via Starcrest Nigeria Energy)	Sugarcane ethanol project	Sugarcane	100 million litres sugar and electricity
Kwara Casplex Ltd/Kwara State Government	Cassava ethanol project	Cassava	38.86 million litres
Ekiti State Government + Private	Oke-Ayedun cassava ethanol project	Cassava	38.1 million litres, biorefinery + farm
Ekiti State Government / CrowNet Green Energy	Ethanol plant	Cassava	65 million litres, 1,100 tonnes of starch and 50 tons of CO_2/day
Taraba state	Cassava ethanol plant	Cassava	72 million litres, 360,000 tonnes of cassava flour, 1.87million tons of CO_2 and 57 Mg/yr of liquid fertilizer, 1600MW
Niger state and others	Niger State Government Ethanol Plant	Cassava	27 million litres, biorefinery + farm (estimated)
Ogun State Government	Cassava Industrialization project	Cassava	3 million litres
Private sector	National Cassakero cooking fuel program	Cassava	1.44 billion litres

Table 2.3: Selected ethanol plants in Nigeria

Name of Company	Plant location	Feedstock	Installed capacity (million litres/year)
Dura Clean	Bacita	Molasses/Cassava	4.4
AADL	Sango Ota	Cassava	10.9
CrowNek	Ekiti	Cassava	64
BV Energy Company	Bayelsa	Cassava	75

2.8 The potential for agricultural residues as feedstocks for cellulosic ethanol production in Nigeria

According to Iye and Bilsborrow (2013a, 2013b), Nigeria has considerable potential for second generation feedstocks for cellulosic ethanol. Agricultural residues, such as sorghum straw, millet straw, rice straw, groundnut straw and maize stalks, as well as cassava and yam peelings are currently underutilized in Nigeria. These are particularly attractive options for cellulosic bioethanol production since they are of relatively low cost and do not imply a fuel versus food conflict, which is a major barrier for first generation biofuels feedstock. Agricultural residues have been identified globally as the most abundant resource for cellulosic ethanol production since they can produce about 442 billion litres of bioethanol per annum (Iye and Bilsborrow, 2013a). In Nigeria, cellulosic ethanol production from agricultural residues accounts for as much as 7556 km^3 per annum, of which 62% of this is from process residues while the rest from the field residues (Iye and Bilsborrow, 2013a).

These feedstocks are currently used in Nigeria as fodder for livestock, organic fertiliser and as cooking and heating fuels for rural areas. Though agricultural residues are used in small industries as fuelwood and charcoal, still a large volume of other resources, such as rice husks, maize cobs, are burnt and buried annually. It is interesting to note that Nigeria has enough agricultural residues to meet its bioethanol target, but the challenges associated with the collection and transportation of large volume of feedstocks from farms to the various locations of the processing facilities remains to be solved. This was therefore the basis for adopting purposely grown energy crops, such as alfalfa, elephant grass, *Miscanthus x giganthus* and switchgrass for this study.

2.9 Switchgrass (*Panicum virgatum L*)

Switchgrass belongs to the "Poaceae" family and is classified as a perennial warm-season C4 grass species native to North America (Daverdin *et al,* 2015). Since the 1980's the crop has been identified to possess a considerable potential for bioenergy production (Hashemi and Sadeghpour, 2013; Rahman *et al*., 2014). The crop can be cultivated on marginal land (Lewis *et al.*, 2014), and has the capability to sequester carbon in the soil to improve soil quality (Arias *et al.*, 2009). Though switchgrass is not necessarily the highest yielding energy crop, it can produce a high yield of biomass under conditions of sufficient water and soil nutrients availability (Fiorese and Guariso, 2010). Additionally, the crop has the capability to adapt in diverse climatic and soil conditions (Lingorski, 2013).

The selection of switchgrass as a potential feedstock for biofuel is based on its specific agronomic, economic and environmental characteristics. For example, the plant has the capacity to grow with low soil fertility and is tolerant to cold, flood and drought *(*Ahrens *et al.*, 2014). Based on the economic benefits, the crop needs low quantities of fertilisers and herbicides (Giannoulis *et al.*, 2009). It is used as a bioenergy crop for cellulosic ethanol, biomass for electricity and heat production, feedstock for diesel fuel, hydrogen and other chemical by-products used in fertilizers, solvents and plastics production (Renz *et al.*, 2009). Switchgrass provides not only economic benefits (Barney and DiTomaso, 2010) but also environmental benefits e.g. carbon sequestration (Hartman *et al.,* 2011).

The development of energy crops on Nigerian farms as a feedstock for biofuels is relevant to recent national and global economic issues. Though switchgrass is not native to Nigeria it has been noted that the use of switchgrass as a biofuel feedstock in the country's agricultural sector can offer great benefits by providing a new source of income to farmers (Abdullahi *et al.*, 2013).

2.10 *Miscanthus x giganteus*

Miscanthus x giganteus is a rhizomatous warm-season grass with C4 photosynthesis originating in South East Asia (Lewandowski *et al.*, 2000; Williams and Douglas, 2011). Miscanthus (*Miscanthus spp.*) is a tall grass species native to Asia, Polynesia, and Africa, while *Miscanthus x giganteus* (*M. giganteus)* is a sterile hybrid of *Miscanthus sacchariflorus (M. sacchariflorus)* and *Miscanthus sinensis* (*M. sinensis)* which originated from Japan. In 1935, miscanthus was introduced to Europe (Erickson *et al.*, 2012) as an ornamental plant (Lewandowski *et al.*, 2003).

In the late 1960s, the first trial experiment on Miscanthus as an energy crop was carried out in Denmark (Lewandowski *et al*, 2003) and has since then received considerable attention as a potential source for renewable energy production (Hodkinson *et al.*, 2002). The increasing interest of *Miscanthus x giganteus* as a C4 biofuel feedstock for renewable fuel production is due to its exceptional biomass yield potential and the capability to adapt to diverse climatic conditions (Widholm *et al.*, 2010).

Among the promising C4 perennial herbaceous crops, Miscanthus has a considerable advantage over other crops as it is easy to grow and harvest and it produces high dry biomass yield (McKendry, 2002). The productivity of the crop is enhanced by high soil organic content together with the availability of adequate rainfall as well as soil pH (Williams *and* Douglas, 2011; McKendry, 2002).

The potential benefits of purposely grown energy crops like *Miscanthus* spp do not only include their use for biomass heat and electricity, but also exhibit the ability for carbon sequestration, reduce the rate of erosion, improve biodiversity and ensure fuel security (Aylott *et al.*, 2012).

2.11 Alfalfa (*Medicago sativa L.)*

Alfalfa is one of the oldest forage crops in the world (Sanderson and Adler, 2008; Deng *et al.*, 2014). Alfalfa is popularly referred as the “king of forages” due to its high productivity and it’s adaptive to diverse soil conditions (Cash, 2009). It is currently cultivated as an energy crop for biofuel production due to its production potential on grassland (Russelle *et al.*, 2007). The crop possesses several benefits which range from environmental to economic benefits (McCaslin and Miller, 2007). Its highly digestible leaf material is used as a forage for animals (Mobtaker *et al.*, 2011). The whole stems can be used as biofuel feedstock as well as extraction of pharmaceutical co-products from the leaf and root materials (Bouton, 2006). According to Jung (2008) alfalfa has been rated as the third most important field crop as a potential feedstock for biofuels. Martin and Jung (2010) reported that alfalfa as an economic crop has the potential to provide the feedstock for cellulosic ethanol production. Alfalfa can also reduce the rate of soil erosion, increase water quality by reducing surface water contamination by nitrate, as well as improve soil organic matter. The production of alfalfa in grassland enhances carbon sequestration (Mobtaker *et al.*, 2011) and can reduce emissions of greenhouse gases in the future (Sanderson and Adler, 2008).

These benefits coupled with the capability to provide an improved forage for livestock production and increased energy balance by fixing nitrogen make alfalfa stand out in biofuel cropping systems (Summers and Putnam, 2008).

2.12 Elephant grass (*Pennisetum Purperum S.)*

Elephant grass originates from the tropical and sub-tropical regions of Africa (Musa *et al.*, 2012). The crop later gained global popularity outside of the continent of Africa in the Central America, part of the tropical Asia, Australia, the Middle East and the Pacific islands as well as North America (US) (Wang *et al.*, 2002) and South America (Brazil) (Vieira *et al.*, 1997).

Tremendous interest has been gained through the use of elephant grass and therefore it is referred to as the world's fastest growing crop. The crop belongs to the perennial herbaceous grass family (Poaceae) (Ohimain *et al.*, 2014). It is a non-edible grass species that has clear potential for biofuel production due to its exclusion from the popular 'food versus fuel' debate (Singh *et al.*, 2013). It is a perennial grass species primarily used as animal feed, mostly in the tropics due to the high yield (Obok *et al*., 2012). Elephant grass has the capacity for CO_2 fixation which enables high biomass yield of about 30 to 60 tonnes/ha per year under appropriate conditions (Ohimain *et al.,* 2014). The successful growth and establishment throughout the year is due to its easy adaptability to a wide range of soil types, high rainfall, temperature requirement as well as the soil pH which ranges from highly acidic to alkaline conditions (Singh *et al.*, 2013). In Nigeria, elephant grass is used as fodder for livestock production due to its high nutritional value (Obok *et al.*, 2012). It is also used for phytoremediation (clean up technique) of petroleum contaminated soils due to high biomass and bioaccumulation factor (Zhang *et al.,* 2010).

The plant is currently used as a potential biofuel feedstock due to its rapid growth and high yield thereby making it a choice candidate for biofuel feedstock that can compete with fossil fuels (Singh *et al.*, 2013).

2.13 Agro-ecological and geographical zones of Nigeria

There are major differences in climate between the different regions of Nigeria which have clear impacts on food production and on the potential for biofuel production. The South observes a long wet season which starts from mid-March until July. It is usually accompanied by heavy rainfall leading into the planting season (Aregheore, 2009). The total annual mean rainfall in the South East varies whereby Owerri (Imo state) experiences about 2,380 mm while Ebonyi and Enugu states record 1,980 and 1,860 mm, respectively (Okonkwo and Mbajiorgu, 2010). The average annual maximum temperature of Nigeria varies from 31^{o}C to 36^{o}C between the North and South regions. The annual minimum temperature range also varies from 18^{o}C in the South to 23^{o}C in the North (Salako, 2008). The Nigerian grassland areas constitute the Northern guinea savannah, Southern guinea savannah, the derived savannah and humid forest zones of Nigeria (Fig. 2.5). Most grasses found in the derived savannah are also found in Guinea savannahs but they appear less fertile (Aregheore, 2009). Tall grasses such as fountain grass (*Pennisetum spp*), gamba grass (*Andropogon gayanus),* elephant grass (*Pennisetum purpureum*), guinea grass (*Panicum maximum*) and southern gamba grass (*Andropogon tectorum*), grow wildly in the derived savannah and Southern guinea savannah zones (Adegbola and Onayinka, 1976).

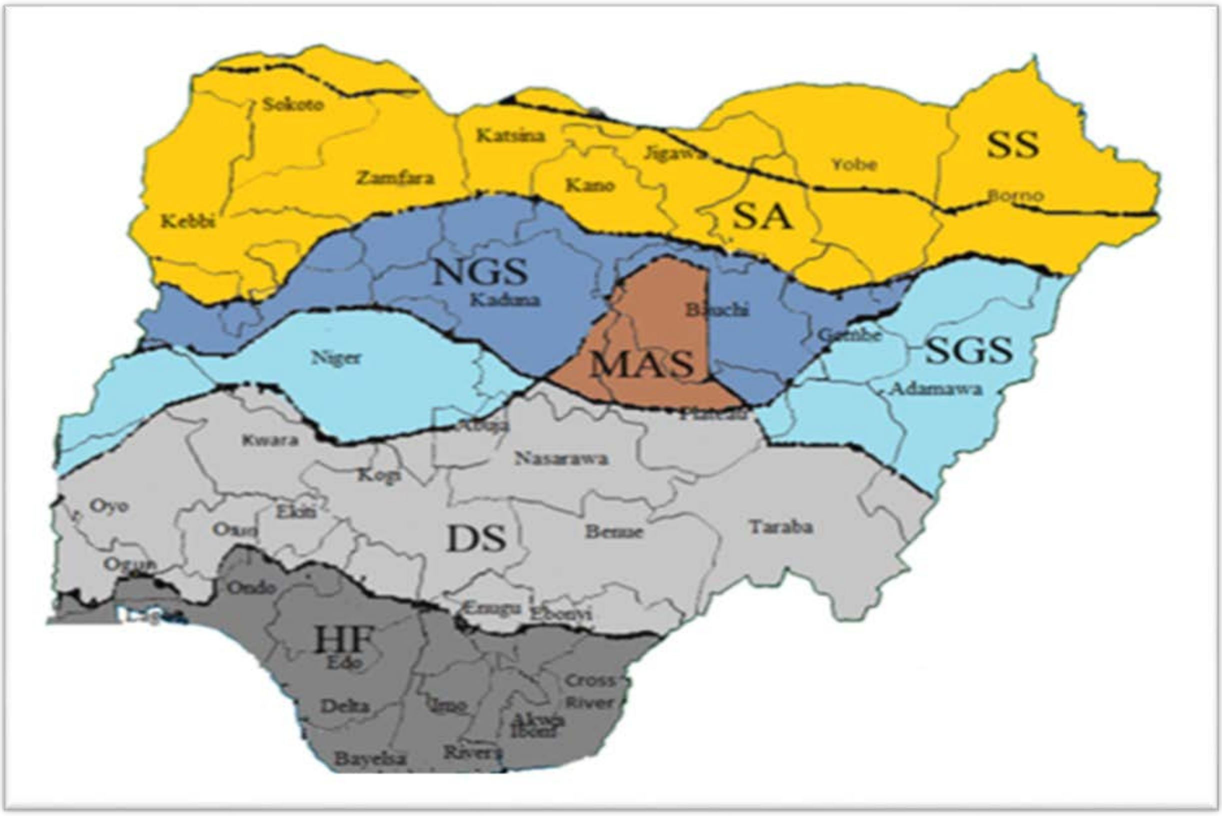

Figure 2.5: The different agro-ecological zones in Nigeria

Note: The locations of different agro-ecological zones are identified as follows. HF: Humid forest zone, DS: Derived savannah zone, SGS: Southern Guinea savannah zone, NGS: Northern Guinea savannah zone, SS: Semi-arid/Sudan savannah zone and SA: Sahel savannah zone.

2.14 Geographical Information System (GIS) based applications for land suitability analysis

In order to assess suitable locations for growing these species, a Geographical Information Systems (GIS) based multi-criteria decision process was employed (Deng *et al*., 2014). Geographical Information Systems are software systems used to visualize, store and manage large data sets for land suitability mapping and analysis, which enables identification of most appropriate locations for future land use (Richard *et al.*, 2009). It can also be defined as a tool used by land-use managers and stakeholders to enable them carry out decisions within a given period of time.

The growing pressure on land resources has motivated the application of GIS to enable identification of suitable areas for sustainable agricultural production (Joshua *et al.*, 2013). Selecting a suitable location for sustainable production will not only address technical requirements but also physical, social, economic and environmental requirements that may cause controversies in achieving the set objectives. Land suitability plays a fundamental role in modern agricultural activities, such as bioenergy crop production, which will require information on agricultural activities like land use, soil and weather conditions (Joshua *et al.*, 2013). Li *et al.,* (2013) states that the production rate of bioenergy crops is associated with several negative impacts, such as biodiversity loss, food scarcity and land use change. Mitchell (2010) also stated that Africa is among the continents that possess a large amount of suitable and available land for biofuel crop production.

Gurgel *et al.,* (2007) have as well stated that GIS and spatial models have been used to assess land availability of bioenergy crop production in Yorkshire and Humber. Such models can estimate the production potential of cellulosic biomass feedstocks from local resources and address the bioenergy land-use problems. It can be used as a basic tool to plan and decide the future land use of biofuels in Africa (Mitchell, 2010; Molony and Smith, 2010).

Heumann *et al.,* (2011) designed the Maximum Entropy (MaxEnt) model which employs defined geographical and environmental conditions to estimate suitable land availability for bioenergy production. The major limitation of this model is the inability to collect data from inaccessible areas like the developing and under-developed worlds. Gurgel *et al.,* (2007) further stated that Computable General Equilibrium (CGE) model has been modified to include multiple agricultural land types, natural areas and future conversion for agricultural land to energy crops. The reason for this modification is to enable the evaluation of cellulosic biomass production in the 21st century, with or without the policy to mitigate greenhouse gas emissions.

The study further stated that the purpose of this modification is to address the limitations of first generation biofuels to the global energy demand.

As inspired by this work used a land suitability model to assess the potential for bioenergy crop production similar to that applied in Yorkshire, United Kingdom. The adoption is based on the ability to analyse future production potential of energy crops for biofuel production in developing countries. Most importantly, the model could serve as a key tool for other African countries to ease the process of complex decision-making regarding future land use planning and biofuel policy development (Molony and Smith, 2010; Mitchell, 2010).

A landscape-based approach that can take into account agricultural productivity and climatic conditions of Nigeria needs to be applied. This means basically to evaluate the potential for the introduction of new crop species at a local level. This method enables the assessment of bioenergy potential from local resources and addresses the land-use problems associated with bioenergy production. A major challenge of GIS and spatial modelling is the ability to generate data required in sub-Saharan Africa where land use and land tenure are complex issues. Therefore, an understanding of current land use systems is required in order to achieve effective results

2.15 Rationale for the study

Nigeria is the sixth largest crude oil producer in the world. Based on the high production, Nigeria established four refineries in Kaduna, Warri and 2 in Port Harcourt to attain its domestic demand. These facilities were to process crude oil components, but perform well below their installation capacities. Due to the constraints surrounding oil production and the poor performance of the refineries, Nigeria employs large amounts of its financial resources to import refined petroleum products, where gasoline (PMS) accounts 70% of the country's total consumption. The increasing rate of PMS consumption contributed to the recent effects of GHG emissions such as flood incidences and coastal erosion, and which have claimed human lives, destroyed properties and farmlands in Nigeria (Otomofa *et al.*, 2015). In order to address these problems, the government decided (in 2007) to diversify its investment into biofuel, but almost the entire pioneer projects were to use cassava as the key feedstocks without considering the fuel versus food conflicts that may arise. Climate change has become the world's most challenging environmental problem, and in 2016 Nigeria signed the Paris Agreement to demonstrate commitment to the global effort to reverse the adverse effects of GHG.

Against this background, several studies that looked at first and second generation biofuel feedstocks have continued to highlight that agricultural land can be used successfully for biofuel feedstock production, however, without identifying where this land will come from.

To this effect, this study "A GIS based approach to investigating the potential of herbaceous energy crop species for cellulosic bioethanol production in Nigeria" aims to fill this gap, by identifying suitable grassland and shrubland for growing non-edible feedstocks for cellulosic bioethanol production. Cellulosic bioethanol could meet the country's energy demand, mainly due to the suitability and productivity of energy crops across entire zones of Nigeria. Moreover, it is without doubt that cellulosic bioethanol from selected energy crops will reduce not only the amount of GHG emissions from land use change but also from the road transport sector if blended with PMS (gasoline), since it has minimal environmental impacts. Also the country's expenditure on PMS imports will be drastically reduced since the feedstocks will be locally sourced and the fuel produced across every region of Nigeria. Finally, successful establishment of a viable biofuel industry in Nigeria will provide sustainable jobs to the increasing population of unemployed youths.

2.16 Specific research objectives

The major research objectives of this thesis are as follows:

1) To investigate the land requirement of selected herbaceous perennial bioenergy feedstocks to support the Nigerian Biofuel Policy;
2) To evaluate the potential of C3 and C4 herbaceous energy crops as feedstocks for cellulosic bioethanol production in Nigeria by geo-political zone and by states
3) To estimate the theoretical ethanol yield and potential processing facilities; by zone and states of Nigeria for the four selected species.

Chapter 3: Methodology

This chapter aims to present the methods used to achieve the research objectives.

3.1 Location

Nigeria exists between latitudes 4º to 14º North and longitudes 2º2' and 14º 30' East and is bounded to the North by the Republic of Chad; west by Benin Republic, while East and South by Cameroon and the Atlantic Ocean, respectively (Aregheore, 2009). Nigerian has one of the largest populations in Africa currently estimated at 182 million people (Financial Nigeria, 2016). From North-South is 1050 km and East-West about 1150 km (Elegbede and Guerrero, 2016).

3.2 Data collection and sources

This research is focused on estimation of the potential of the selected four herbaceous perennial bioenergy feedstocks for cellulosic ethanol production in Nigeria. The secondary data including Land Cover of Nigeria, Digital Elevation Model (DEM), climate and soil data were obtained from various organisations via websites and by personal communication. The Land Cover data of Nigeria for 2009, which was originally developed by Globcover (a Global Land Cover Network for multi-purpose Land cover data production), was obtained from the Food and Agriculture Organisation of the United Nation (FAO)[2]. According to the Meta data from the globecover regional (Africa) archive, the data was classified as valuable information for natural resource and environmental studies. It is the most current and recent land cover data (2005) as at the time of this study and had a resolution of 300 meters on global land cover dataset scale. Moreover, the data is promoted by the Global Land Cover Network (GLCN) to

[2] available at http://www.fao.org/geonetwork/srv/en/resources.get?id=37204&fname=nga_gc_adg.zip&access=private)

make it satisfactory and acceptable with GLCN standards and usable for the purpose of land cover based analysis and modelling[2].

Beside the fact that this data was from a reputable agency (United Nation; FAO), it was also recommended by Dr Phil James an expert and a senior lecturer in Geographical Information Science from the School of Civil Engineering and Geosciences, Newcastle University. The quality and processing of the land cover data was also confirmed by Darrien Pugh a certified GIS expert from Lovell Johns Limited. It was based on these recommendations that the data was used as a baseline for this study.

The Digital Elevation Model (DEM) for 2008 was obtained from the Shuttle Radar Topography Mission (SRTM)[3]. The climate data for the 36 states and Federal Capital Territory (FCT) for the four year period (2010-2013) was sourced from the Nigerian Meteorological Agency (NIMET).

Soil data for 2005 and livestock datasets by state for 2008-2011 were obtained from the Nigeria Programme for Food Security (NPFS) and the Federal Department of Animal Production & Husbandry Services (FDAPHS); under the Federal Ministry of Agriculture and Rural Development (FMARD) respectively (Table 3.1).

[3] http://srtm.csi.cgiar.org and the Administrative Map of Nigeria (AMN) obtained from DIVA-GIS; http://www.diva-gis/datadown).

Table 3.1: Sources of datasets

Factor	Parameter	Sources
Climate	Temperature and rainfall data	NIMET
Soil	Soil pH and Organic Carbon	NPFS- FMARD
Topography	Elevation and slope	SRTM
Livestock	Cattle, goat and sheep	FDAPHS- FMARD
Land cover	Originally 46 classes	FAO Archive

Various data sets on soil type and characteristics were employed in order to determine the best area for growing the specified bioenergy crops taking into account the agronomic needs of each crop. Information on land and crop productivity of each zone were also obtained which enabled identification of the areas associated with grassland and shrubland. Also, the soil requirements of each species was based on geo-morphological variables, which included slope and elevation. Soil organic matter and soil pH are the two soil fertility classes used while, the climate variables include, temperature and rainfall. These factors were integrated into ArcGIS (ESRI) version 10.2.1 software to evaluate land suitability for each of the proposed four crop species for biofuel feedstocks in the six geo-political zones. The suitable land area is intended to be achieved by subtracting the unsuitable land area from the identified total country areas and the remainder identified as that suitable for each species.

Also a careful comparison of the benefits between the current land use and the production of bioenergy crops will be considered, thereby outlining the preference between bioenergy crops and the major national agricultural crops. The essence of this selection is to avoid the 'food versus fuel' debate arising from the use of cropland and staple food crops for biofuel production. There have been serious concerns about the increasing competition for food markets due to their use for bioenergy in North America (Fiorese and Guariso, 2010) and in other countries.

3.3 Tools and techniques for data analysis

The following tools and techniques were used to achieve the specific research objectives of this study:

- Geographical Information System (GIS) is software used to store, process and format data, to enable presentation and evaluation of all spatial information.
- Multi-Criteria Decision Method (MCDM*)* is an operational research model used in addressing complex problems with different forms of data and information. The process combines and transforms spatial datasets to facilitate and make valuable judgement (Meng *et al.*, 2011), in order to provide solutions to complex decisions and problems (San Cristóbal, 2012).
- Analytical Hierarchy System (AHP) is one of the MCDM approaches introduced by Saaty (1987). It is the most widely accepted and reliable MCDM employed to carry out important decision making processes on land suitability planning and allocation (Saaty, 1987).
- Python software is a modern and excellent mainstream programming language mainly for scientific codes. The programme is fast enough to be used immediately with expressive syntax of an interpreted language (Oliphant, 2007). Python was adopted since it can be easily embedded within existing software such as ArcGIS to carry out productivity analysis.

3.4 Justification for choosing grassland and shrubland

The idea for choosing grassland and shrub land is due to the global acknowledgement that the development of bioenergy crops should not compete with land that is already in use for food production and the need to ensure that land is not made available for use resulting from deforestation (Zhang *et al.*, 2016) because of the potential for significant increases in Greenhouse Gas Emissions (GHG). Bare land was excluded from this study since the area is small, i.e. only 4.6% of the total country area.

3.4.1 Grassland

The land use classification of Nigeria shows that 17% of the area is covered by grassland (Abbas *et al*., 2018). According to Aregheore (2009) Northern Nigeria based on its low rainfall is mainly a savannah land, which comprises 80% of the total country vegetation zones. The savannah contains about 80% of the total population of grazing livestock in Nigeria. The Derived Guinea Savannah zone was initially classified as the drier part of the Guinea savannah (high forest) as a result of long time bush burning, cultivation, hunting and over grazing activities in the area.

The savannah land is characterized by tall grasses like *Pennisetum Purpureum* (Clifton-Brown and Valentine, 2007), *Panicum maximum* (guinea grass) and is used as a natural habitat for livestock production (Aregheore, 2009). The grazing of goats, horses, sheep, cattle, camels and donkeys are mostly carried out by the Nomadic herders from the North in an extensive grazing based system. Grasslands are also used by some local populations for hunting (Aregheore, 2009) activities. Therefore, since grassland in Nigeria is presently largely underutilized, a certain percentage of the area could be used for biofuel crop development.

3.4.2 Shrubland

Shrubland comprises of woody shrubs and can provide habitat for native plant and animal species (Shaffer *et al.*, 2012). For this study shrubland is included for the potential development of biofuel crops as land that is currently underutilized, since no official publications have been able to separate the area of shrubland from natural grassland in Nigeria. The areas are concurrently used for the same purpose i.e. extensive grazing of livestock.

3.5 Processing of land cover data

Step 1: Conversion of land cover data of Nigeria

The land cover (LC) of Nigeria layer file (Fig 3.1) was converted to both vector and raster formats (Fig 3.2A and B) respectively. The essence of this conversion was to allow for an effective and flexible use of the two data formats during processing and analysis. The vector format enables classification of data into three geometrical shapes, including line, point and polygon. The polygons are used to determine the particular areas associated with each geographical feature. The raster formats which consist of digital images and cells is a map algebra (ArcGIS Spatial Analysis tool) used to carry out raster calculations (Liao *et al.*, 2012). The cell-based raster datasets are most suitable for the representation of traditional geographic data i.e. elevation, slope and temperature. Raster datasets are also considered as the most appropriate tool for spatial modelling and suitability analysis (Liao *et al.*, 2012).

Step 2: Raster cell size

During rasterization, the standard resolution (300m) for multi-purpose LC datasets provided by the Global Land Cover Network (GLCN) was adopted as the cell size due to the extent of the study area. The geographic extent of the country was changed from geodesic to planar during rasterization to convert the unit of the shape file from decimal degrees (DD) to meters (m). A section of the rasterized data was selected and the input cell size (300m) measured to obtain an output cell size of 298m which is equivalent to the original cell size. The essence of this measurement was to compare and confirm the accuracy of the output cell size and the reliability of the approach.

Step 3: *Spatial reference system*

The spatial reference of LC layer file with a World Geodetic Survey 1984 (WGS84) was changed to Universal Transverse Mercator (UTM) projected co-ordinate system.

The WGS84 is a terrestrial reference system used to define real world points located on the earth's surface. It involves a consistent set of parameters that explains the nature of the Earth's surface either through the earths shape or area. The conversion to UTM was to identify the points representing the earth, which is in round shape and translate them to a flat 2-dimensional surface such as a piece of paper.

Step 4: Aggregation and reclassification of feature classes to seven target classes

The original 49 LC classes (Table 3.1) were aggregated and reclassified into 24 classes by default during the process. The 24 default classes were further re-classified into seven classes, comprising of both the vector and raster formats (Fig. 3.2 A&B) respectively. The rationale behind the reclassification to seven target classes was to allow identification of areas that can be utilized for biofuel crop development as well as areas that were excluded from the study based on current use and preferences. Generalization method was used to reclassify the feature classes, where all irrigated areas, mosaic and rain fed land were classified as cropland. The mosaic vegetation with canopy cover of 50-70% were classified as grasslands, closed to open broadleaved evergreen forest greater than 40% were classified as forest land, closed to open deciduous and evergreen shrubs with < 5 metre height classified as shrubland, the open land with a cover canopy of less than 15% was classified as bare land, all permanently or temporary flooded areas were classified as water bodies while the associated surface areas were classified as built-up areas (Appendix 4). During the final reclassification process, ArcGIS Field calculator was used to create a new field and write a script command for each feature class as follows; “VALUE=11 OR VALUE=14 OR VALUE=20” to derive a class name e.g. “cropland”. This was carried out subsequently to systematically reclassify and derive the remaining class names and generate the seven target classes: “bare area”, “built-up area,” “cropland” “forest”, “grassland”, “shrubland” and “water bodies” (Fig. 3.2B).

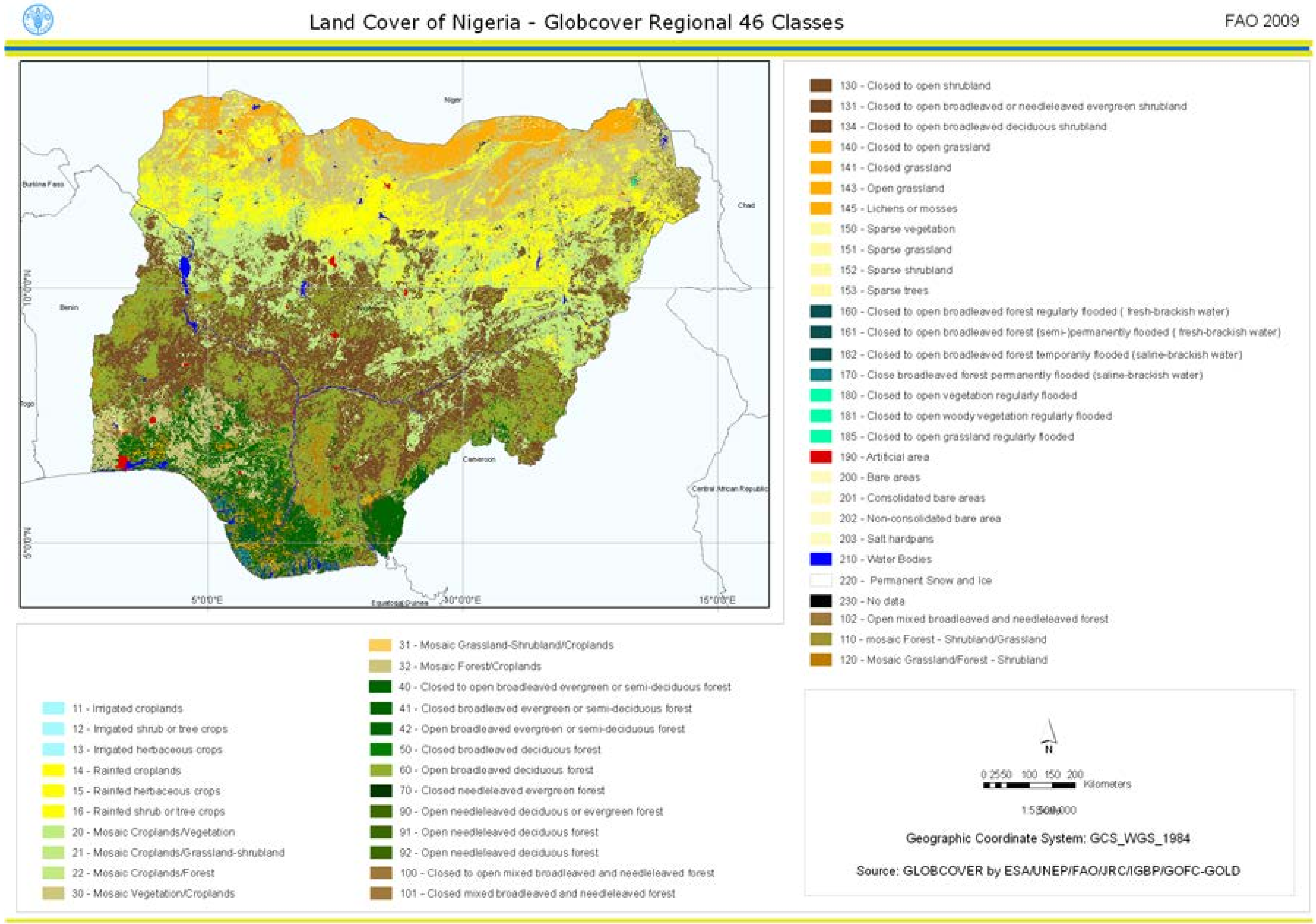

Figure 3.1: Original land cover classes before rasterization (Latham, 2009).

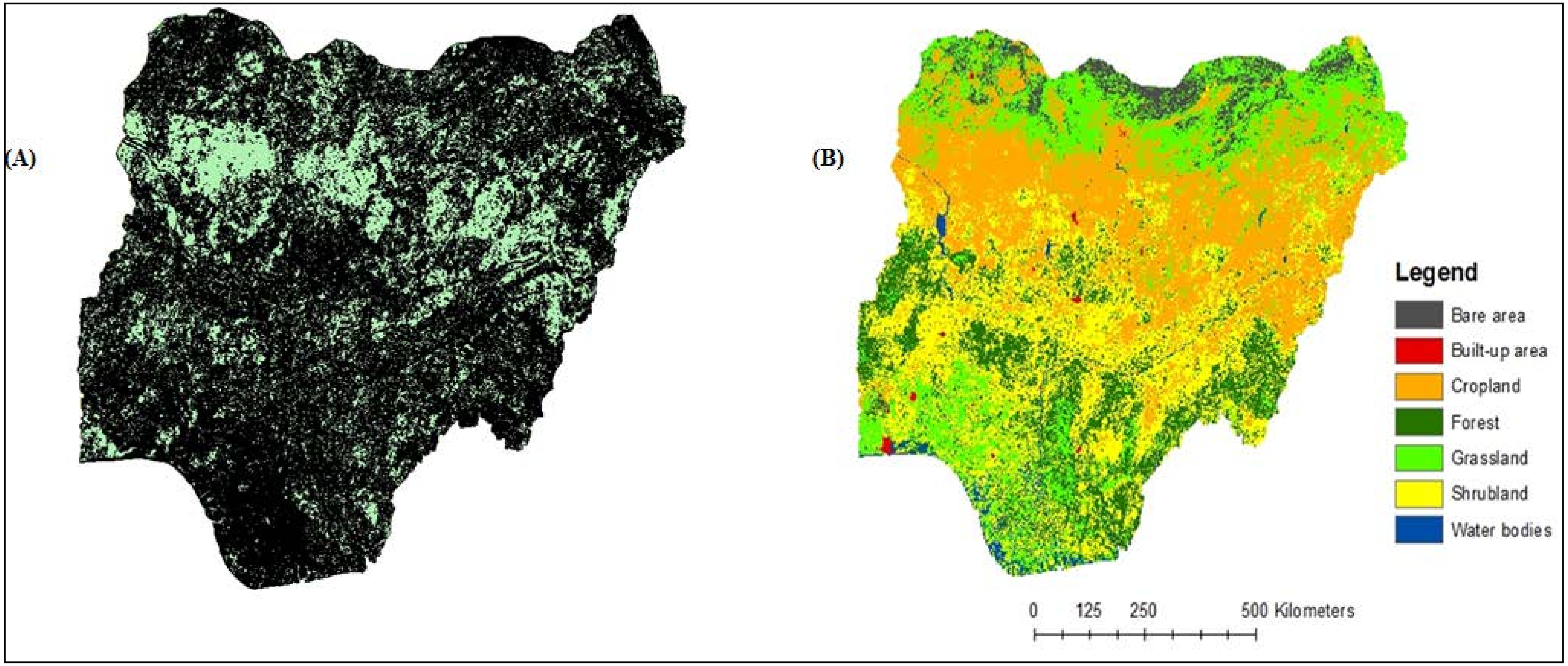

Figure 3.2: Vector and Raster formats of the Nigerian land cover.

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Step 5: Evaluation of LC areas based on the UTM projection system

In order to evaluate areas of each LC class, the cell counts were viewed in the layer properties and datasets exported to an excel spread sheet. The total number of counts for each LC was multiplied by the cell size (300m x 300m) to estimate areas of each LC within a total country area of 940,878 km^2 (Table 3.2). The country area in square meters (m^2) was converted to standard units, i.e. square kilometres (km^2) and hectares (ha).

In estimating LC area using the UTM projection system, cropland was identified as covering about 48% (444,332km^2) of the total country area, forest about 21% (191,018km^2), grassland and shrubland 10% (93,763km^2) and 22% (200,559km^2) respectively. The bare land and built-up areas accounted for 0.2% of the country area each while water bodies accounted for 1.0% (8,884km^2) of the total country area (Table 3.2).

A discrepancy discovered was that the rasterized GIS figure (940,878km^2) for the total country area was over 3% higher than the input shape file (909,436km^2) obtained by checking the individual polygon areas and also the official recorded land area of and the official Nigerian land area (909,890km^2) as cited in the Nigerian Annual Abstract of Statistics (NAAS) (2012).

However, further estimation using Africa Albers Equal Area Conic (AAEA) projection system was recommended due to the discrepancies discovered and its suitability to minimize area distortions across datasets in GIS based analysis (Dickens, 2016)

Table 3.2: Evaluation of LC areas based on ArcGIS and UTM projection systems

Land cover	**Count**	**Cell size**	**Cell size**	**Area (m^2)**	**Area (km^2)**	**Area (ha)**	**% of total land area**
Bare area	2417	300 x 300	90000	217530000	218	21753	0.02
Built-up area	23358	300 x 300	90000	2102220000	2102	210222	0.2
Cropland	4937025	300 x 300	90000	4.44332E+11	444332	44433225	47
Forest	2122424	300 x 300	90000	1.91018E+11	191018	19101816	20
Grassland	1041815	300 x 300	90000	93763350000	93763	9376335	10
Shrubland	2228437	300 x 300	90000	2.00559E+11	200559	20055933	21
Water bodies	98721	300 x 300	90000	8884890000	8885	888489	0.9
					940,878	**94,087,773**	**100.0**

Step 6: Reclassification and evaluation of LC classes using the AAEA projection system

In order to re-calculate the country area, a similar approach was employed to reclassify the 46 classes and re-project from UTM to AAEA using the Polygon to Raster tool. The 24 rasterized classes were further reclassified to the same 7 classes using Field calculator. Field statistics were viewed after changing the "Symbology" to observe the total cell counts for each LC. Although, the cell counts were not multiplied with the cell size to estimate areas of LC, rather the ArcGIS Dissolve tool was used to carry out the estimations. The essence of using the 'Dissolve' tool was because it was faster and more straightforward than using excel spreadsheet to calculate the areas.

The datasets were first ran into a Raster to Polygon tool to convert the cells or pixels to shape file before the Dissolve tool was used to estimate attribute areas of each LC class. The dissolved areas in square meters (m^2) were exported into an excel spreadsheet and the unit converted to square kilometres (km^2) and hectares (ha) respectively. Each LC was estimated and a total country area of 909,400 km^2 (Table 3.3) obtained which was much more accurate than the previous estimation (942,878 km^2) carried out using the UTM projected system. The figure of 909,400 km^2 was equivalent to the 909,435km^2 obtained by checking the input attribute areas of the LC shape file. The new country area (909,400km^2) was also observed to be much closer to the official published figure of 909,890km^2, and the approximated 91.07 million hectares (Mha) (Aregheore, 2009). The estimated areas of the seven LC using the UTM projected system indicated that 48% of the country area was cropland and 21% forest. These projected figures were significantly higher than the 31% of cropland and 15% of forest land obtained using the AAEAC projected system. The estimated cropland (31%) and forest (15%) were more in line with the 36% of cropland and 15% forest identified in other publications (Vermehren and Ofosu-Amaah, 2006).

Similar results indicated that arable land accounted for 35%, pasture 15% and forest 10% of the country area (Aruofor, 2001; USAID, 2016). However, whichever projection was used to create a single raster of any large area, certain spatial distortions would definitely occur into the raster. Therefore, for the purpose of an area-based GIS analysis, a suitable equal area projection was recommended to avoid area-distortions across the dataset extent. The similarity between the estimated values using the AAEA projection system and other published figures confirm the accuracy of the adopted approach in this study.

Table 3.3: Estimated LC areas of Nigerian based on ArcGIS and AAEA projection system

Land cover class	No of count	Cell size	Area (m^2)	Area (km^2)	Area (ha)	% total area
Bare area	466742	90000	4.2E+10	42007	4200678	4.6
Built-up area	22555	90000	2.03E+09	2030	202995	0.2
Cropland	3172091	90000	2.85E+11	285488	28548821	31
Forest	1515592	90000	1.36E+11	136403	13640324	15
Grassland	2089348	90000	1.88E+11	188041	18804130	21
Shrubland	2673726	90000	2.41E+11	240635	24063537	26
Water bodies	164397	90000	1.48E+10	14796	1479573	1.6
				909401	90940056	100

Step 8: Evaluation of Nigerian LC areas by state using the AAEA projection coordinate system

In order to clip and calculate areas of each LC for the 36 states and FCT of Nigeria, the administrative map of Nigeria (AMN) was overlaid with the primary output data. Each state was selected from the Attribute Table (AT) and highlighted to export to the default geo-database (gdb). The essence of exporting to gdb was to create a shape file that was used to clip each dataset out from the national LC scale using Raster clip (an ArcGIS Data management tool).

The clipping process for the entire 36 states and the FCT were subsequently carried out before these were ran through the Raster to Polygon tool and each LC area calculated using the Dissolve tool. The dissolved datasets for all the 36 states and FCT were exported from the attribute table to excel spread sheets to carry out further processing and estimate the areas. According to the results, Borno state was discovered to possess approximately 16% (30043km^2) of the total country grassland and 3.1% (7402 km^2) of shrubland. Niger state accounted for approximately 12% (28555 km^2) of total country shrubland and total grassland of 0.7% (1384km^2) (Table 3.4). Taraba was observed as another interesting state with approximately 11% of shrubland (25223km^2), although with only 1.3% (2473km^2) of grassland (Table 3.4). It was also discovered from the estimation that Anambra and Abia states possess the least country grassland and shrubland. Anambra state accounted for only 0.8% (1479 km^2) of grassland and 0.3 (716 km^2) of shrubland (Fig. 3.4) while Abia state had 0.5% (869 km^2) of grassland and 0.7% (1674 km^2) of total country shrubland. From the preliminary evaluation, it was observed that Borno, Niger and Taraba states could provide the most potential grassland and shrubland area to be exploited for bioenergy crop development in this study.

Table 3.4: Areas of grassland and shrubland by state and FCT

State	Grassland (km^2)	Shrubland (km^2)	% Shrubland	% Grassland	% Shrubland Grassland
Borno	30043	7402	15.90	3.10	19.00
Niger	1384	28555	0.70	11.90	12.60
Taraba	2473	25223	1.30	10.50	11.80
Yobe	20901	727	11.10	0.30	11.40
Bauchi	10582	6387	5.60	2.70	8.30
Kwara	1987	16836	1.10	7.00	8.10
Oyo	3035	14002	1.60	5.80	7.40
Sokoto	13797	144	7.30	0.10	7.40
Edo	6366	8954	3.40	3.70	7.10
Katsina	13454	21	7.10	0.00	7.10
Nasarawa	300	16464	0.20	6.80	7.00
Benue	942	15030	0.50	6.20	6.70
Zamfara	11464	833	6.10	0.30	6.40
Kaduna	784	13705	0.40	5.70	6.10
Ogun	7385	5255	3.90	2.20	6.10
Ondo	6444	6020	3.40	2.50	5.90
Jigawa	10553	140	5.60	0.10	5.70
Kogi	1722	11650	0.90	4.80	5.70
Delta	4923	5712	2.60	2.40	5.00
Kebbi	7460	1918	3.90	0.80	4.70
Cross River	2641	7241	1.40	3.00	4.40
Adamawa	796	9160	0.40	3.80	4.20
Plateau	1383	7706	0.70	3.20	3.90
Osun	3962	3970	2.10	1.60	3.70
Kano	6053	609	3.20	0.30	3.50
Bayelsa	3555	2711	1.90	1.10	3.00
Rivers	2038	3203	1.10	1.30	2.40
Ekiti	2158	2248	1.10	0.90	2.00
FCT	101	4465	0.10	1.90	2.00
Ebonyi	676	3683	0.40	1.50	1.90
Enugu	1743	2491	0.90	1.00	1.90
Akwa	907	2541	0.50	1.10	1.60
Imo	1673	1381	0.90	0.60	1.50
Gombe	1744	1102	0.90	0.50	1.40
Abia	869	1674	0.50	0.70	1.20
Anambra	1479	716	0.80	0.30	1.10
Lagos	1096	779	0.60	0.30	0.90
Total area	188873	240658	100.00	100.00	

Step 9: Evaluation of LC areas by geopolitical zone using the AAEA projection system

To enable the estimation of each LC area for the six geopolitical zones of Nigeria, the administrative map of Nigeria was overlaid with the primary output data and all the states in each zone selected from the Attribute Table (AT). The highlighted states were merged to produce each geopolitical zone before these were exported to a file geo-database (gdb). The dissolved LC areas in square meters (m^2) were subsequently converted to square kilometres (km^2) and hectares (ha) (Appendix 5-16). According to the preliminary results of LC area on a zonal basis, Nigeria possesses a total grassland and shrubland area of approximately 428,503 km^2 (47%) of total country area, of which grassland accounts for about 21% (187,996 km^2) and 26% (240,507 km^2) is shrubland (Table 3.5). The North East (NE) zone has the highest area with over 35% (66,544 km^2) and approximately 21% (50004 km^2) of total country shrubland and grassland respectively (Table 3.5). The North Central (NC) zone accounts for the highest shrubland in Nigeria with approximately 42% (100,718 km^2) but with only 3.7 % (6,919 km^2) of grassland (Table 3.5). The North West (NW) zone is another interesting zone which accounts for 34% (63,571 km^2) of grassland and 7.2% (17,371 km^2) of shrubland (Table 3.5). The South West was identified to possess the highest grassland and shrubland in the South of Nigeria. The SW zone accounts for over 26% of the country grassland and shrubland with approximately 13% (24,087 km^2) and 13.4 % (32,100 km^2) of grassland and shrubland respectively (Table 3.5). The South South (SS) zone possesses the second largest grassland and shrubland across the South of Nigeria, 11% (20,433 km^2) of grassland and 13% of shrub land. The South East (SE) zone possesses the least potential grassland and shrubland area to be exploited for bioenergy crop development in this study. The SE zone accounts for only 8.1% (16,389 km^2) of the total country area, with about 3.5% (6,442 km^2) of grassland and 4% (9,947 km^2) of shrubland (Table 3.5).

Table 3.5: Grassland and shrubland areas in the six geopolitical zones of Nigeria

Zone	Grassland (km^2)	Shrubland (km^2)	% of Nigeria grassland	% of Nigeria shrub land
South East	6442	9947	3.5	4.1
South South	20433	30367	10.8	12.6
South West	24087	32100	12.8	13.4
North Central	6919	100718	3.7	41.9
North West	63571	17371	33.8	7.2
North East	66544	50004	35.4	20.8
Total	**187996**	**240507**	**100**	**100**

3.6 Formatting and interpolation of climate data

Step 1. Climate data comprising of monthly maximum and minimum temperatures and rainfall for 2010 - 2013 was obtained from the Nigerian Metrological Agency. The climate data for the 36 states and FCT was restructured and integrated with the 39 meteorological stations (including their respective longitudes and latitudes). Datasets were classified into two categories: monthly and annual classes. The three dimensions of the data variables were interpreted as longitude represented by “x”, latitude as “y” and climate (including maximum temperature, minimum temperature and rainfall) as the “z” axis.

The individual climate datasets which consist of the monthly maximum and minimum temperatures across the 36 states and the Federal Capital of Nigeria from 2008 to 2013 were restructured using excel spread sheet (Appendix 19). The essence of restructuring the climate data was to allow a conversion from quantitative format to point shape file using ArcGIS software.

*Step 2***.** The formatted data was added in Arc map to Display X, Y point shape file to a matrix format (Fig 3.6A). The unknown coordinate system was defined by selecting the world geodetic system 1984 (WGS84) from the ArcGIS spatial reference properties.

*Step 3***.** A geo-statistics interpolation method for modelling values (kriging) was employed to interpolate the matrix data using spatial analyst toolbox. The Digital Elevation Model (DEM) obtained from the Shuttle Radar Topography Mission (SRTM) was used to select the extent of Nigeria. The essence of using DEM was to cover beyond the country boundary to enable appropriate clipping of data and avoid potential loss of data in these areas.

Step 4. The administrative map of Nigeria was later used to clip the interpolated area of Nigeria and the reference system projected to AAEA (Fig 3.6 B, C and D). The Resample (Data Management) tool was used to change the output cell size parameter from 6658.8m^2 to 300m^2, before the entire 36 state and FCT of Nigeria were clipped. The essence of resampling from 6658.8m^2 to 300m^2 was to convert all the datasets to the same cell size and ensure that the extents of both the national and state datasets aligns properly with other parameters. This procedure was carried out sequentially for both the rainfall (Fig 3.6B) as well as maximum (Fig 3.6 C) and minimum (D) temperature datasets for 2010-2013.

3.6.1 Interpolation of climate data based on 39 meteorological stations and 37 states

The x, y, z point shape file comprising of 39 meteorological stations and 37 states distributed across Nigeria (Fig 3.3) was used to interpolate the various climate datasets. Jigawa and Bayelsa were the two states without a meteorological station while states such as Ondo, Oyo, Osun and Niger have two stations each. This data enabled identification of state boundaries and location of the meteorological stations.

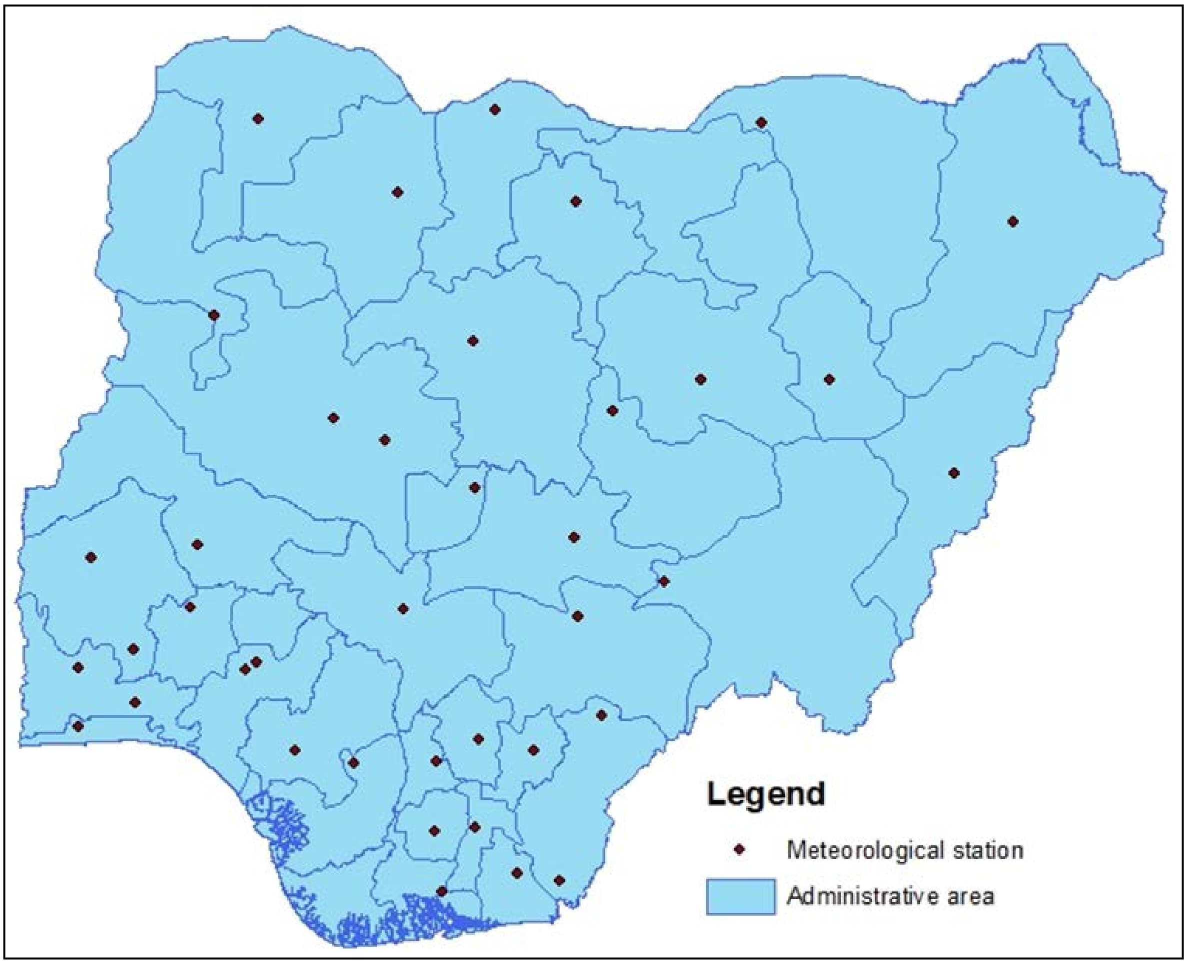

Figure 3.3: Administrative areas of Nigeria with 36 states and location of the 39 meteorological stations.

3.6.2 Formatting and interpolation of climate data

The datasets were interpolated and the 36 states and FCT clipped.

The monthly average and accumulated rainfall over a period of 6 years were calculated using ArcGIS Raster calculator by summing each month and then dividing by the total number of data sets (6) over a period of 2008 to 2013 (the most recent data available at the time of the study). This enabled calculation of mean monthly rainfall over the six year period

$= \frac{\sum x \ (2008 + 2009 + 2010 + 2011 + 2012 + 2013)}{6}$ where, x = monthly rainfall.

According to the results of the evaluations, the monthly maximum and minimum rainfall recorded in July varied between 153 and 423mm while the average annual rainfall estimated over a period of six years (2008-2013) varied between 817 and 2241mm.

The monthly mean temperature was also calculated by summing the monthly maximum temperature (T_{max}) and minimum temperatures (T_{min}) for 2008 to 2013 and dividing by the total number of years

3.7 Evaluating suitable climate (temperatures) for growing the selected four bioenergy crops

Temperature is the major factor that determines the actual life-cycle duration of a crop and how fast it will grow (Hollinger and Angel, 2013). The study reported that there are three cardinal temperatures that determines the climatic conditions of a location and growth of various crop species. Cardinal temperature is referred as the minimum, maximum and optimum temperatures at which different species can germinate. Minimum temperature is the temperature at its lowest range from which crops can grow whereas maximum temperature is the highest temperature at which plants do not thrive (Taghvaei *et al.*, 2015). Temperature varies from place to place and from season to season with considerable differences across the coast, plateau and the lowland areas of Nigeria.

To this effect, the mean annual temperature across the plateau varied between 21^{o}C and 27^{o}C while in the lowlands, the mean annual temperature is 27^{o}C with lower temperatures alongside the coastal fringes. In Nigeria, temperature is generally high throughout the year due to the geographical location and is therefore likely to support the growth of C4 crop species. Daily maximum temperatures can exceed 35^{o}C to 38^{o}C based on region (Aregheore, 2009) which are likely to inhibit the growth of some crops depending on species.

3.7.1 Temperature distribution in the North Central (NC) zone

The temperature distribution in the North Central (NC) geopolitical zone was observed to be highest in April and May with minimum (Tmin) and maximum temperatures (Tmax) of 30 to 31.3^{o}C and 24.2^{o}C to 24.1^{o}C respectively (Fig 3.4). The period of February – May showed the highest monthly mean temperatures but this was also matched by the month of October. A rapid decrease in temperature was recorded around July, August and November with similar minimum and maximum temperature of 22 to 26^{o}C respectively (Fig 3.4). This zone was classified to have a highly suitable temperature since there was no record of any limiting monthly mean temperatures 32^{o}C or below the threshold of 6^{o}C.

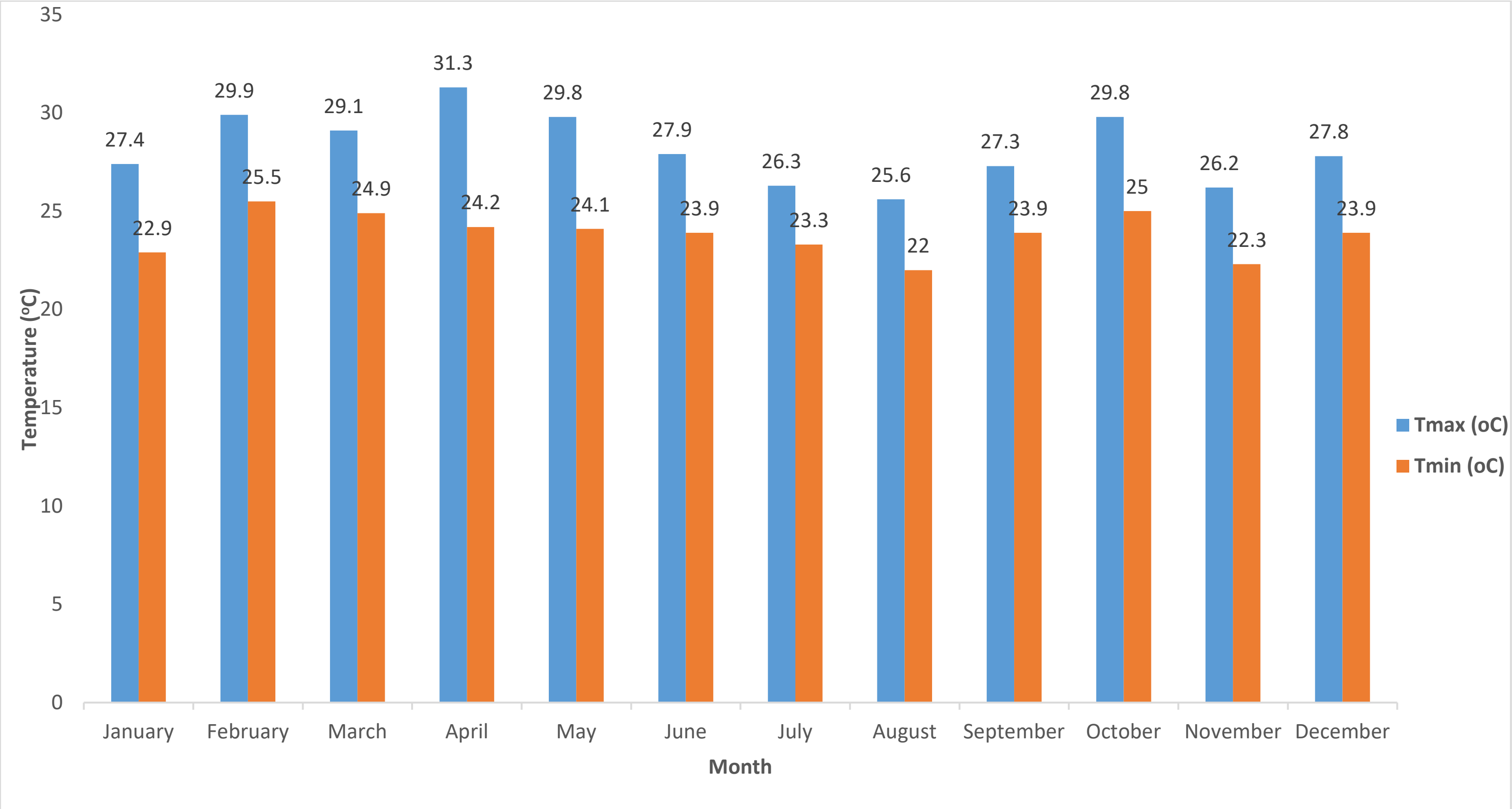

Figure 3.4: Monthly 6-year (2008-2013) mean temperature (Tmax and Tmin distribution across the North Central (NC) Geopolitical zone of Nigeria.

3.7.2 Temperature distribution in the North East (NE) zone

The monthly mean temperature in the NE zone is relatively similar to the NC zone. The study indicated that April and May had the highest maximum temperature of 32.9^{o}C and 31^{o}C (Figure 3.5). The minimum temperature recorded in the NE zone was 22.2^{o}C in August which is unlikely to limit the growth of any of the four species.

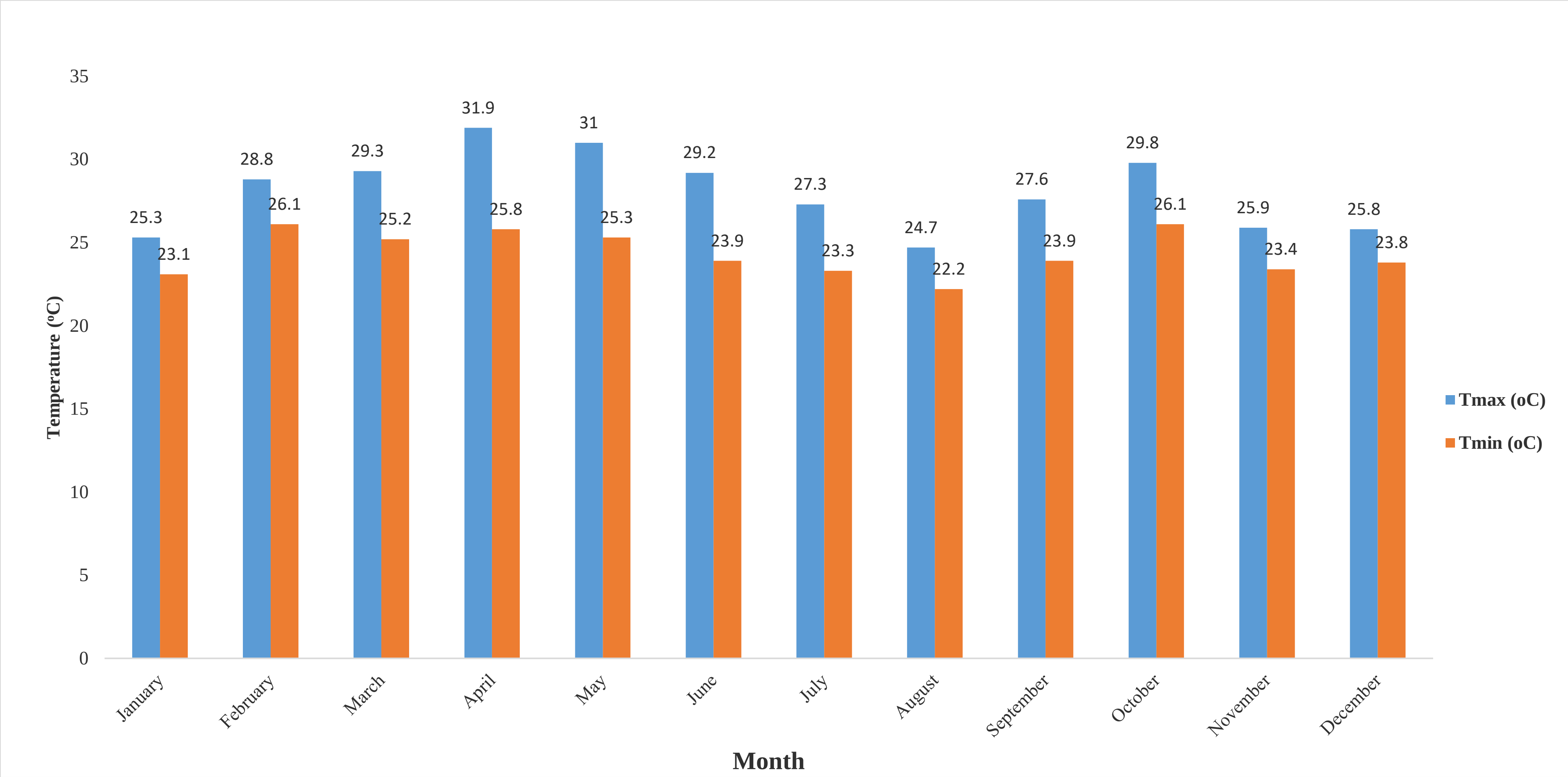

Figure 3.5: Monthly 6-year mean (2008-2013) Tmax and Tmin across the North East (NE) geopolitical zone of Nigeria.

3.7.3 Temperature distribution in the North West (NW) zone

The NW zone was also identified as having a promising climate for growing the selected C4 and C3 species based on the temperature distribution across the area. The optimum temperature was observed from February to June. April and May had average maximum temperatures of 31 to 32^{o}C and minimum temperatures of 27 to 28^{o}C. Further optimum temperature was observed around October with 29^{o}C and a minimum temperature of 26^{o}C. July and August which is the peak of the wet season showed a decrease in temperature. Based on these evaluations, the entire NW zone along with the other Northern zones classified as highly suitable for growing both the C3 and C4 warm-seasons crops (Fig 3.6).

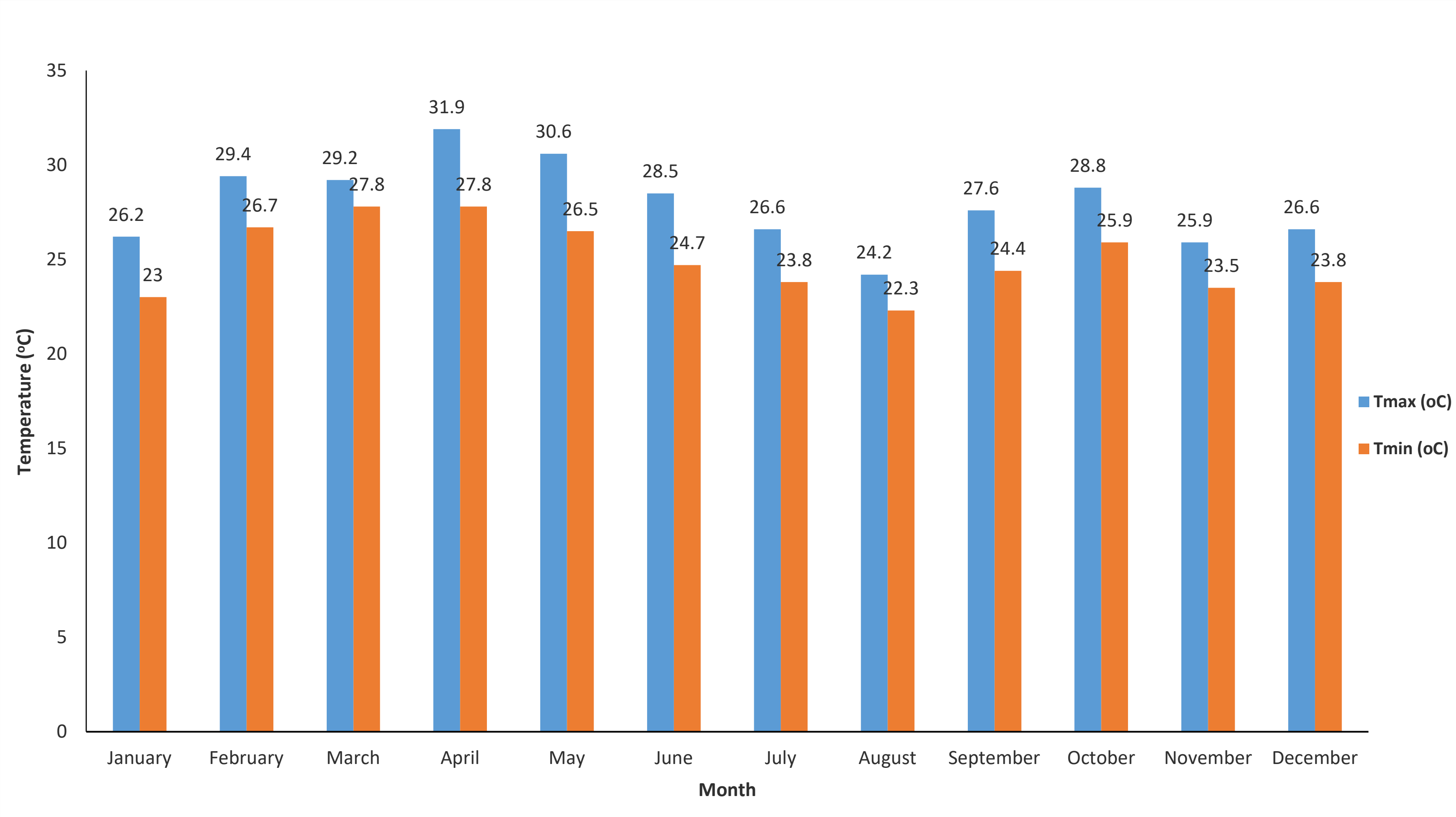

Figure 3.6: Monthly 6-year mean (2008-2013) Tmax and Tmin across the North West (NW) geopolitical zone of Nigeria

3.7.4 Temperature distribution in the South East (SE) zone

The climate conditions of the SE zone is generally less intensive than the North, where a maximum temperature of 32°C was recorded. Like the North zones, the SE zone recorded average minimum monthly temperatures of 17.5 to 24.5 in November (Fig 3.7). Because the SE zone has maximum temperature less than 27.3^{o}C, this therefore indicated that the zone has the capability to support the production of both the C3 and C4 species.

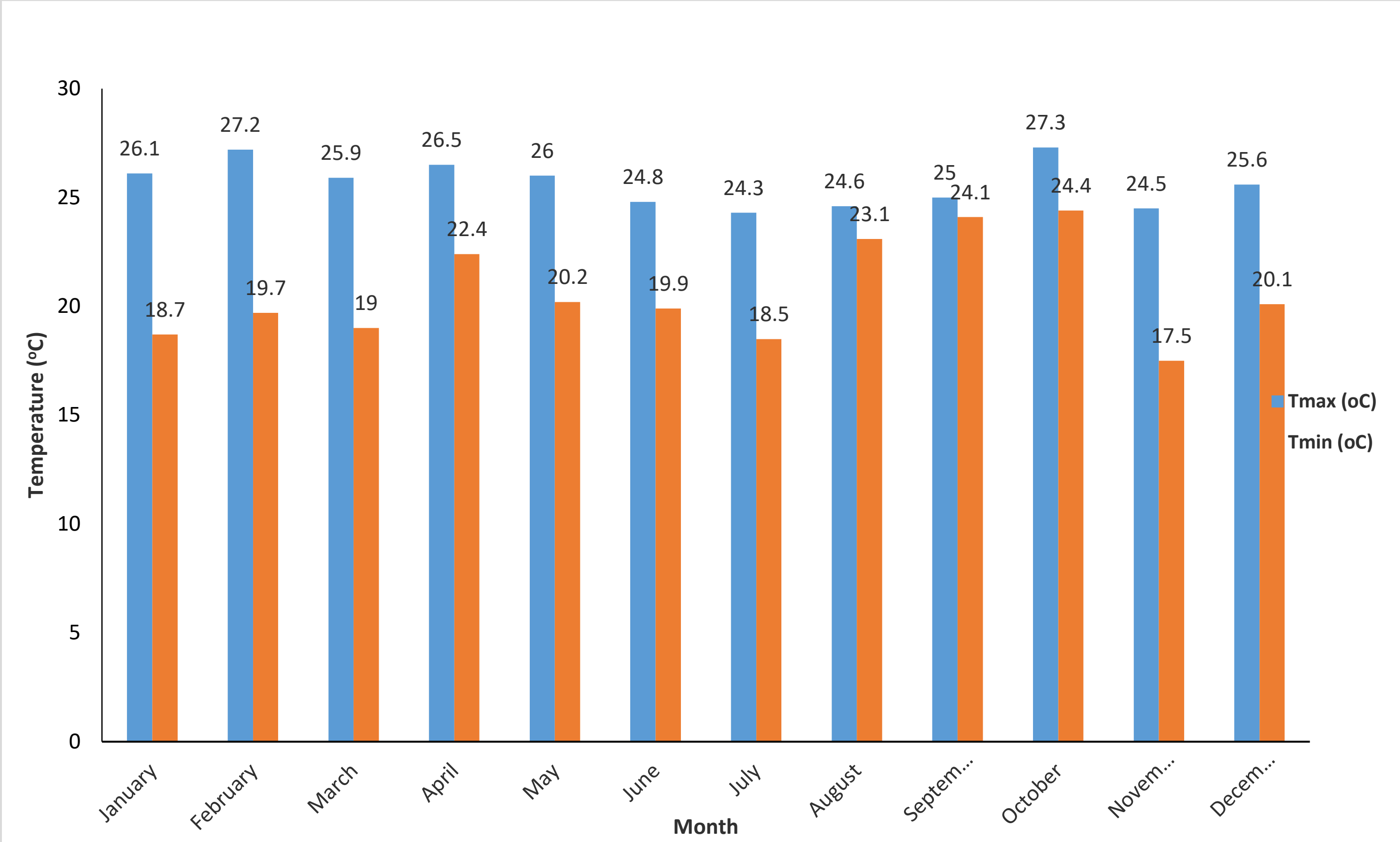

Figure 3.7: Monthly 6-year mean (2008-2013) Tmax and Tmin temperature distribution across the South East (SE) geopolitical zone of Nigeria.

3.7.5 Temperature distribution in the South South (SS) zone

There was little temperature variation in the SS zone, this was rather more favourable for the growth of all the C3 and C4 species. It was observed that the zone recorded optimal temperatures throughout the entire cycle (Fig. 3.8). There was a smaller variation in the average maximum temperature from 25.6^{o}C in August to 29.5^{o}C in February, while mean minimum temperature only varied from 22.6^{o}C in November to 24.7^{o}C in February (Fig. 3.8).

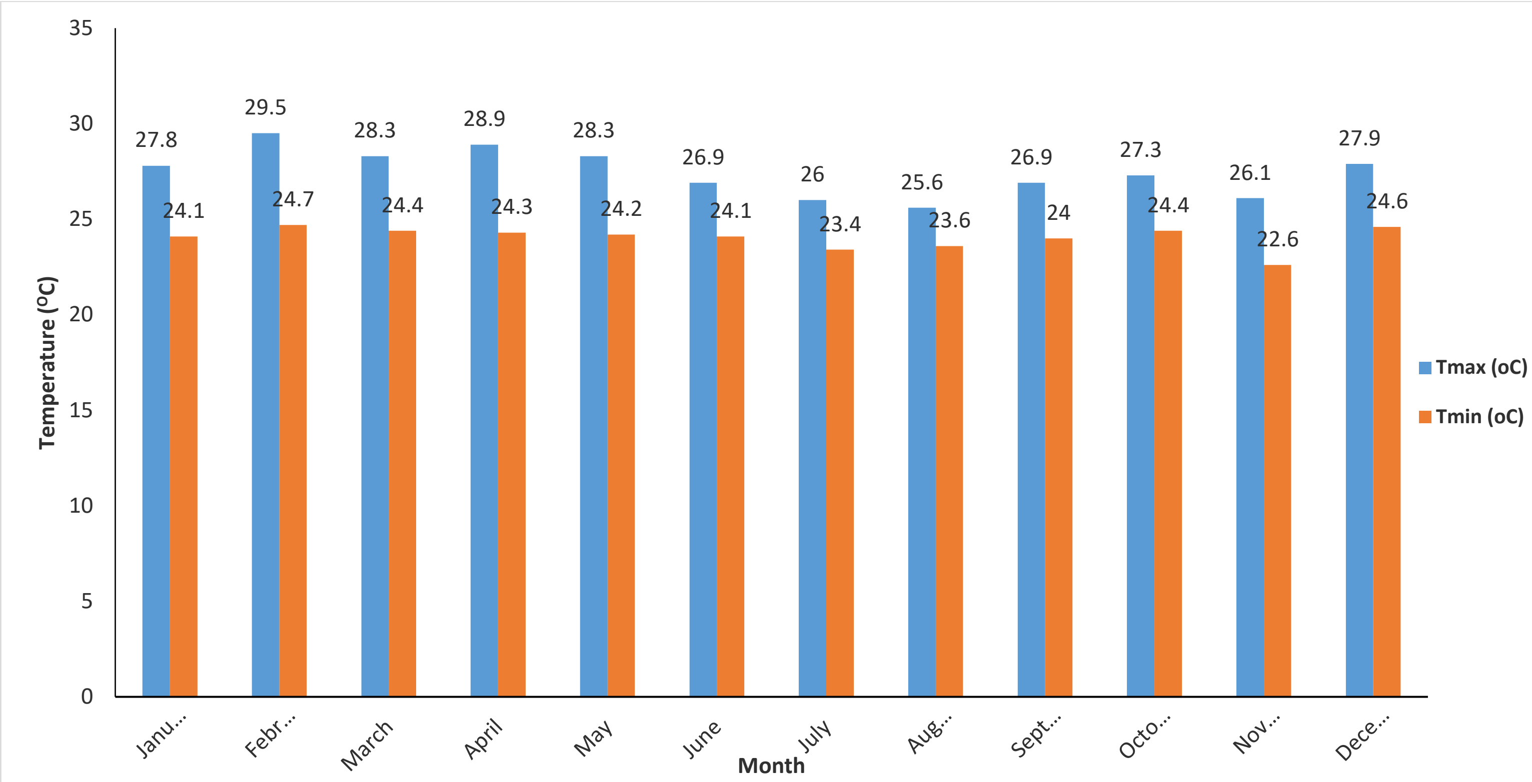

Figure 3.8: Monthly 6-year mean (2008-2013) Tmax and Tmin temperature distribution across the South South (SS) Geopolitical zone of Nigeria.

3.7.6 Temperature distribution in the South West zone

The SW zone is characterized by an average maximum temperature range of 29.5^{o}C in February to 25.5^{o}C in August, with a minimum temperature range of 28.9 to 23.0 ^{o}C for the same months (Fig 3.9). This implies that the entire zone has suitable temperature for all the selected species. According to the results of this study, the entire six geopolitical zones of Nigeria were identified to be suitable for growing C3 and C4 warm-season crops. This is because the zones were identified to possess ideal conditions at minimum and maximum temperatures from 21 to 28^{o}C, which supports the cultivation of the species. Based on the results, there were little or no temperature variations across the SW zone, since the average Tmin and Tmax in the zone is 23 to 30^{o}C (Fig 3.9). Therefore at such condition, the zone would virtually support the production and growth of both C3 and C4 species.

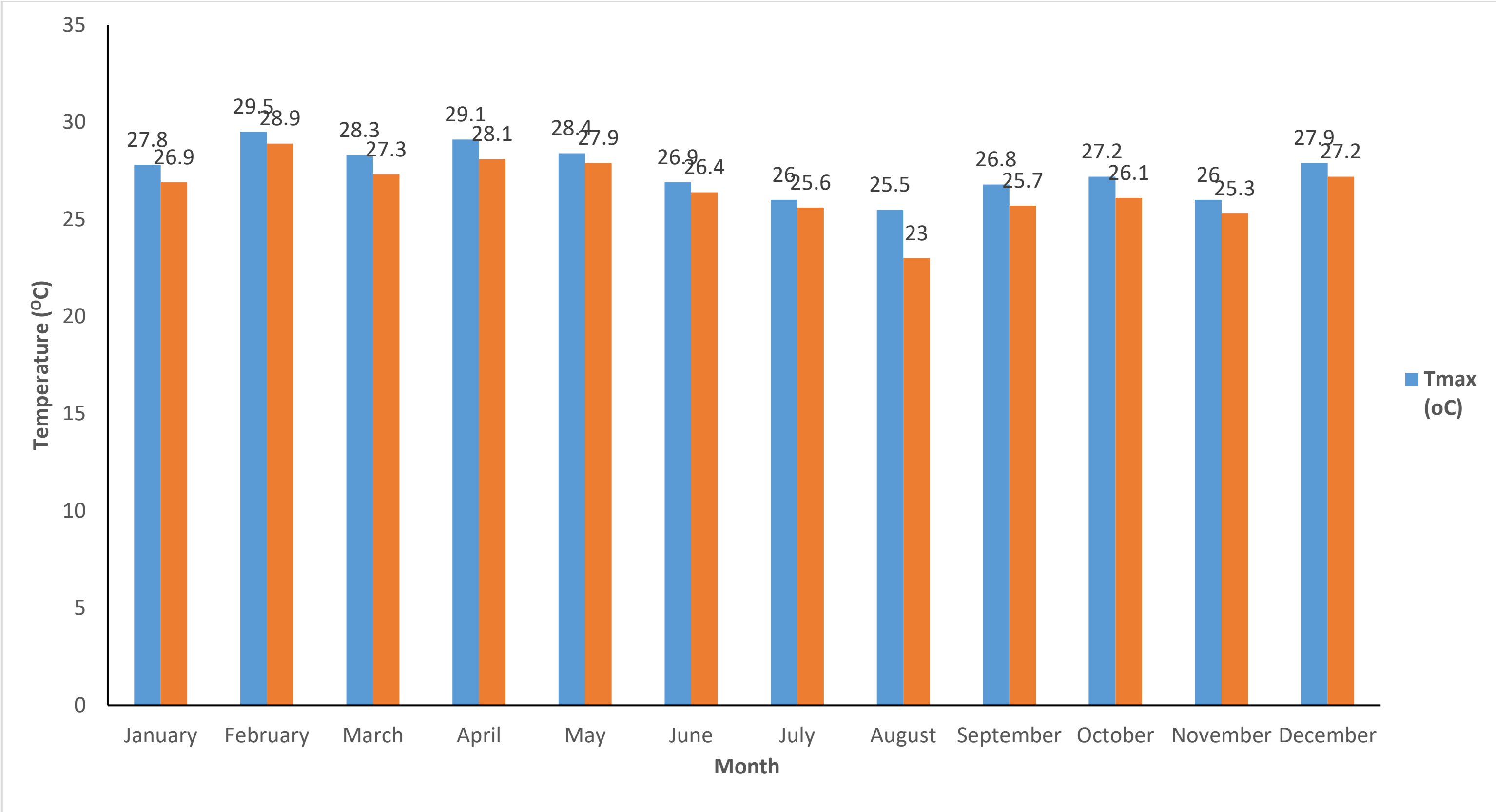

Figure 3.9: Monthly 6-year mean (2008-2013) Tmax and Tmin temperature distribution across the South West Geopolitical zone of Nigeria.

3.7.7. Evaluating the rainfall distribution across the six geopolitical zones for growing the selected bioenergy crops

The annual accumulated rainfall distribution in Nigeria increases from the Sahel desert of the extreme North to the humid tropical savanna region. Rainfall increases progressively from April to October with August and July recording the highest amount of rain in both the North and South respectively (Fig 3.10). The core north comprising of the major part of the North West and the North East zones were identified to record a rainfall range of 800 to 1102 mm. However, large part of the North central zone records about 1100 to 1380, extending from Kaduna state as well as Taraba and Adamawa states in the North west and North East geopolitical zones respectively (Fig 3.10).

The South South and the South Eastern geopolitical zones were indicated to have optimal rainfall distribution of 1699 to 2241mm per annum, with rain decreasing from the South West zone to about 1362 mm per annum (Fig 3.10-11).

Across Northern Nigeria, August has been identified to possess the highest rainfall, with the North Central, North East and the North West zones to record about 296, 294 and 306 mm.

In the South, the optimal monthly rainfall is usually experienced in July with the South South recording the highest rain at 423 mm, the South East with about 306mm while the South West zone records the least with 296 mm (Fig. 3.13-16).

Therefore, according to the results of the analysis, the entire geopolitical zones are presumed to be suitable to support the production of the four bioenergy crop species.

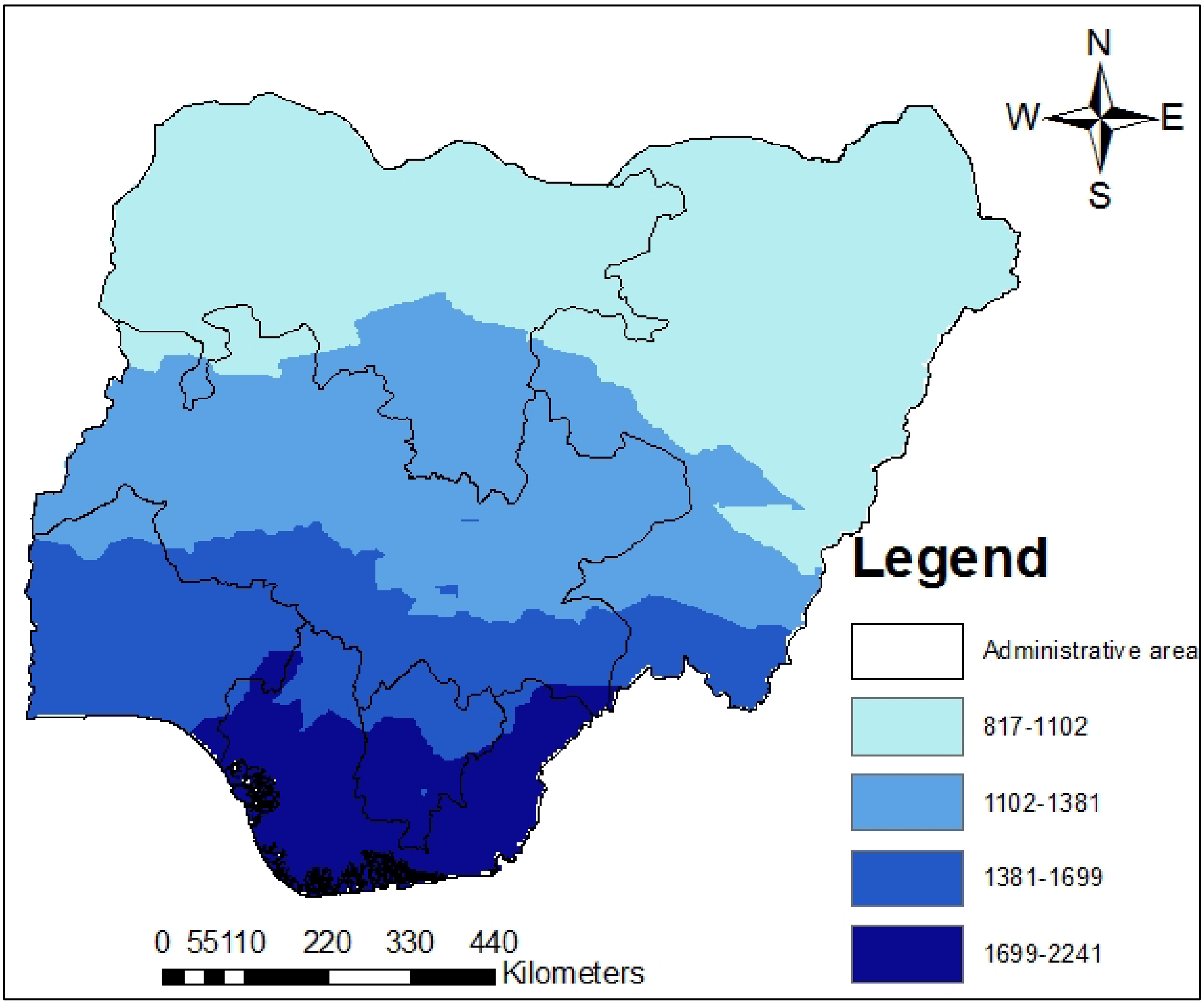

Figure 3.10: Accumulated rainfall by the six geopolitical zones of Nigeria (mm).

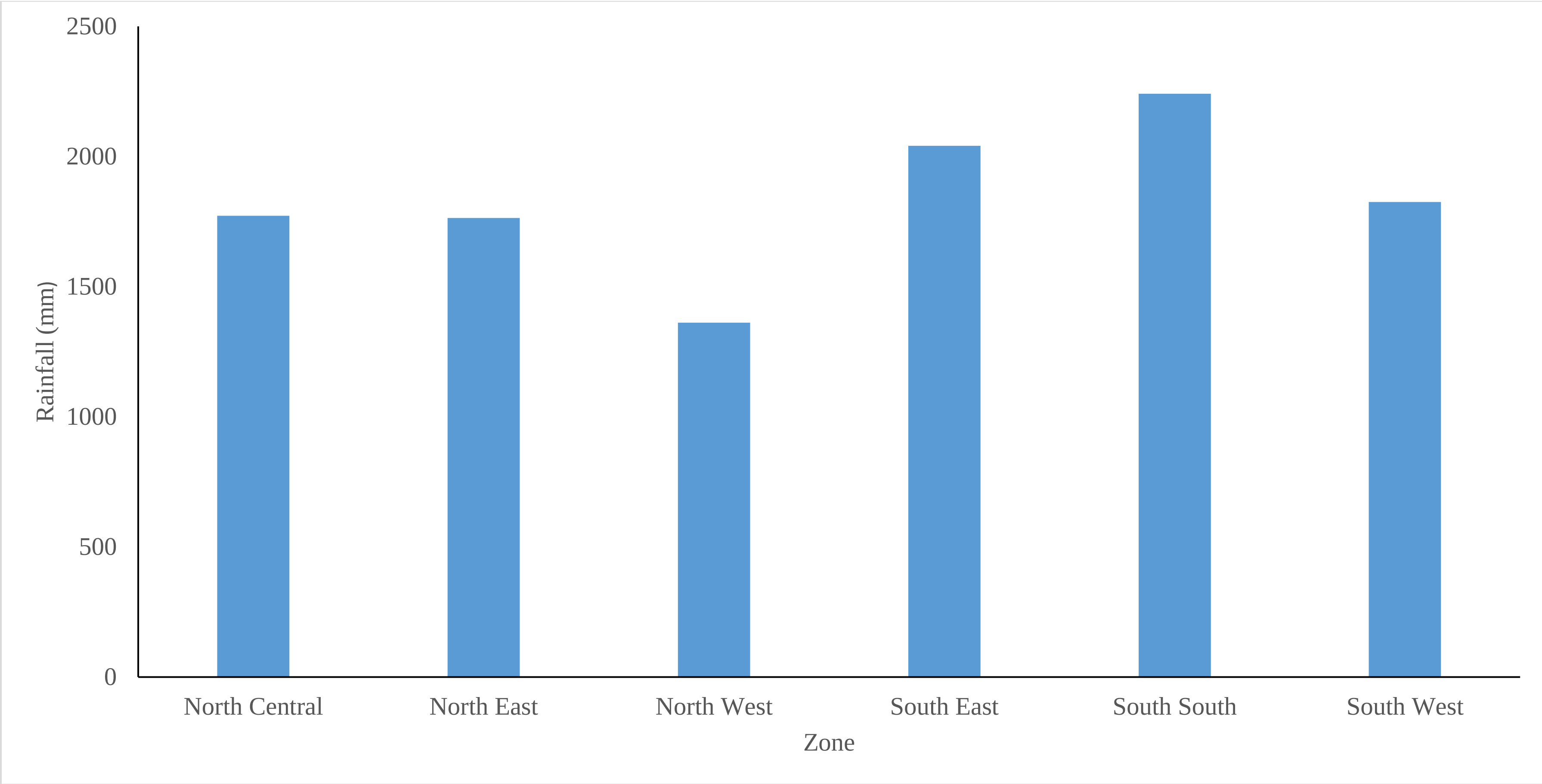

Fig 3.11: Accumulated annual rainfall by the six geopolitical zones of Nigeria distribution by the 6 geopolitical zones of Nigeria (mm)

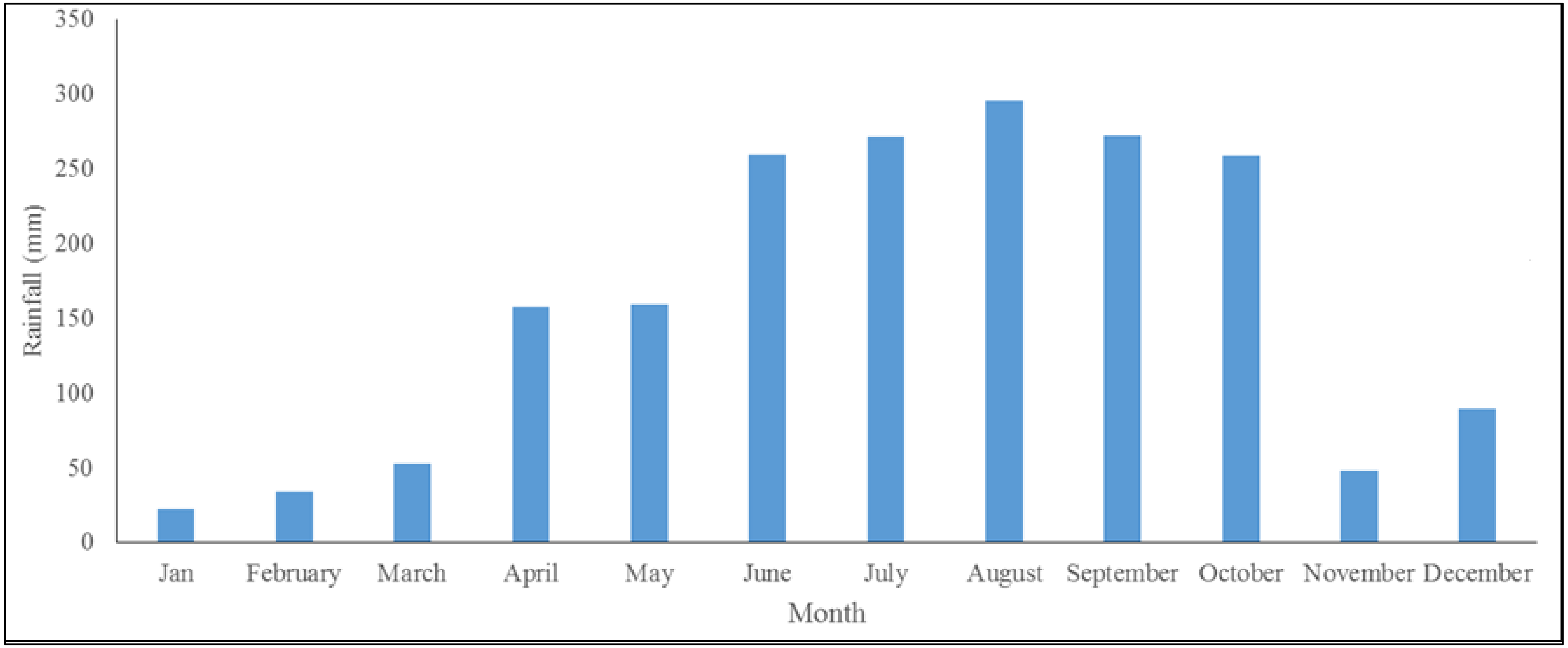

Figure 3.12: Monthly 6-year mean (2008-2013) rainfall (mm) across the NC Geopolitical zone

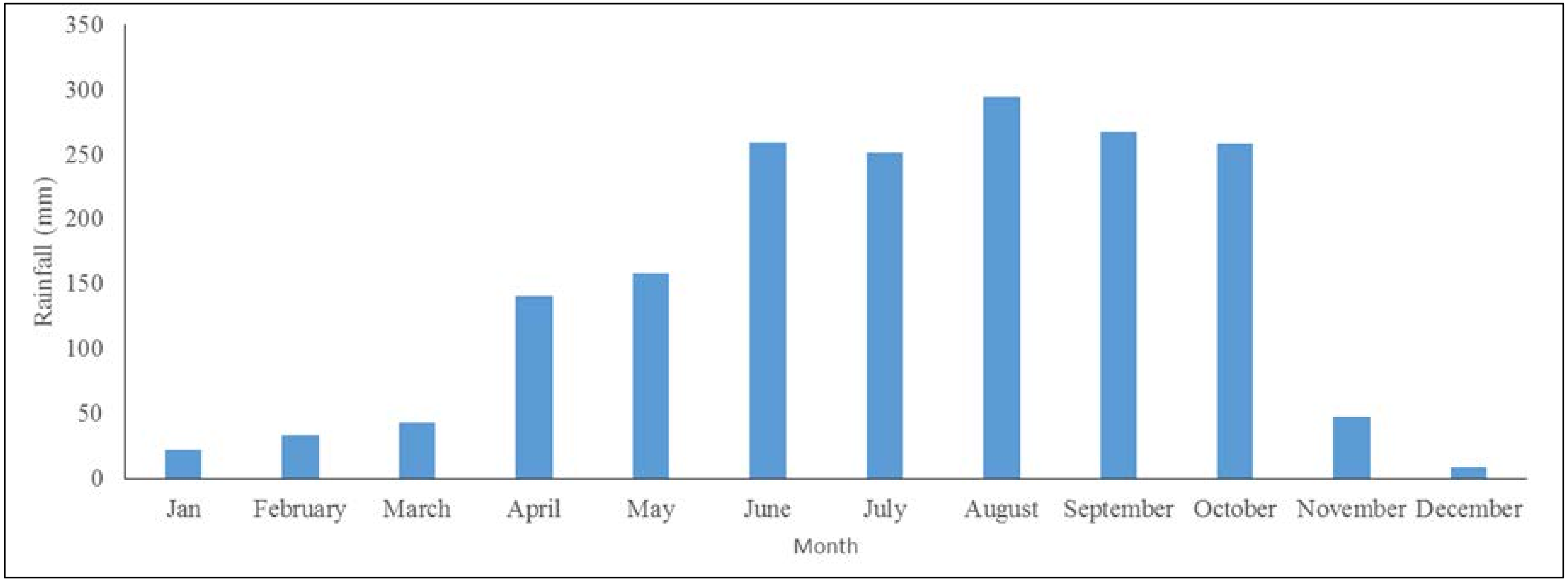

Fig 3.13: Monthly 6-year mean (2008-2013) rainfall (mm) across the NE Geopolitical zone

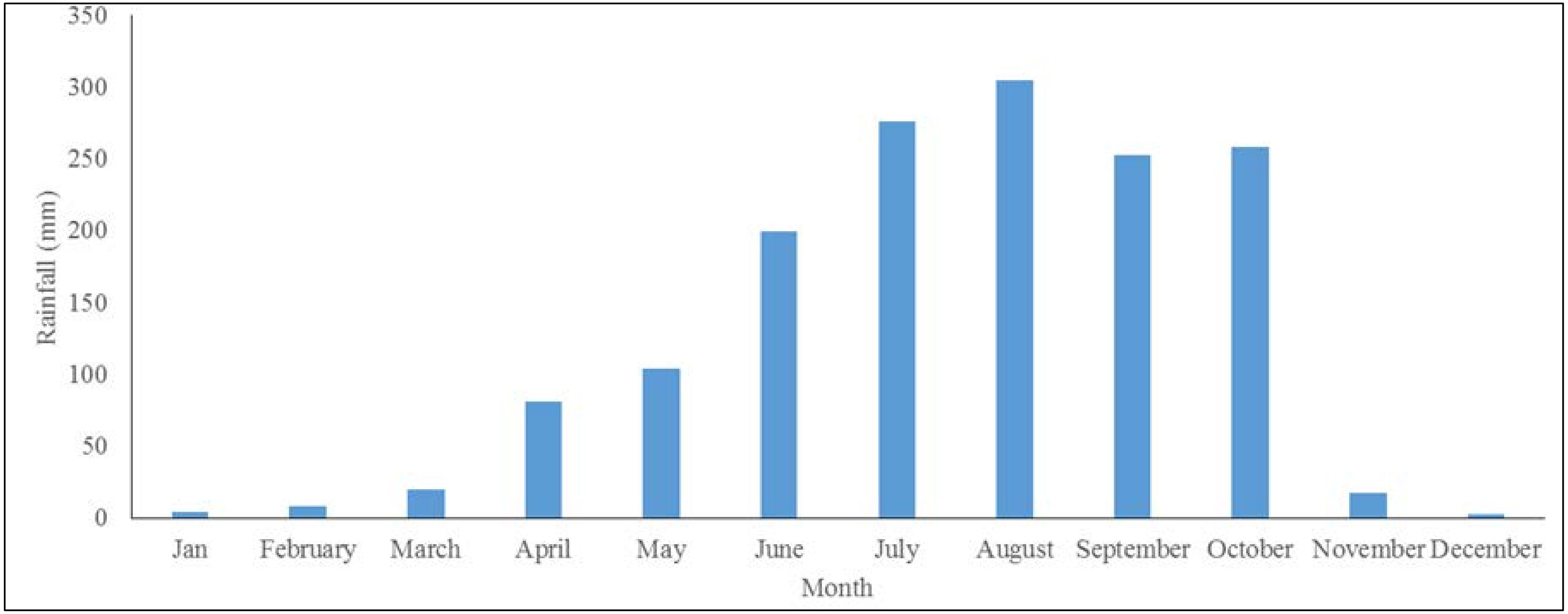

Fig 3.14: Monthly 6-year mean (2008-2013) rainfall (mm) across the NW Geopolitical zone

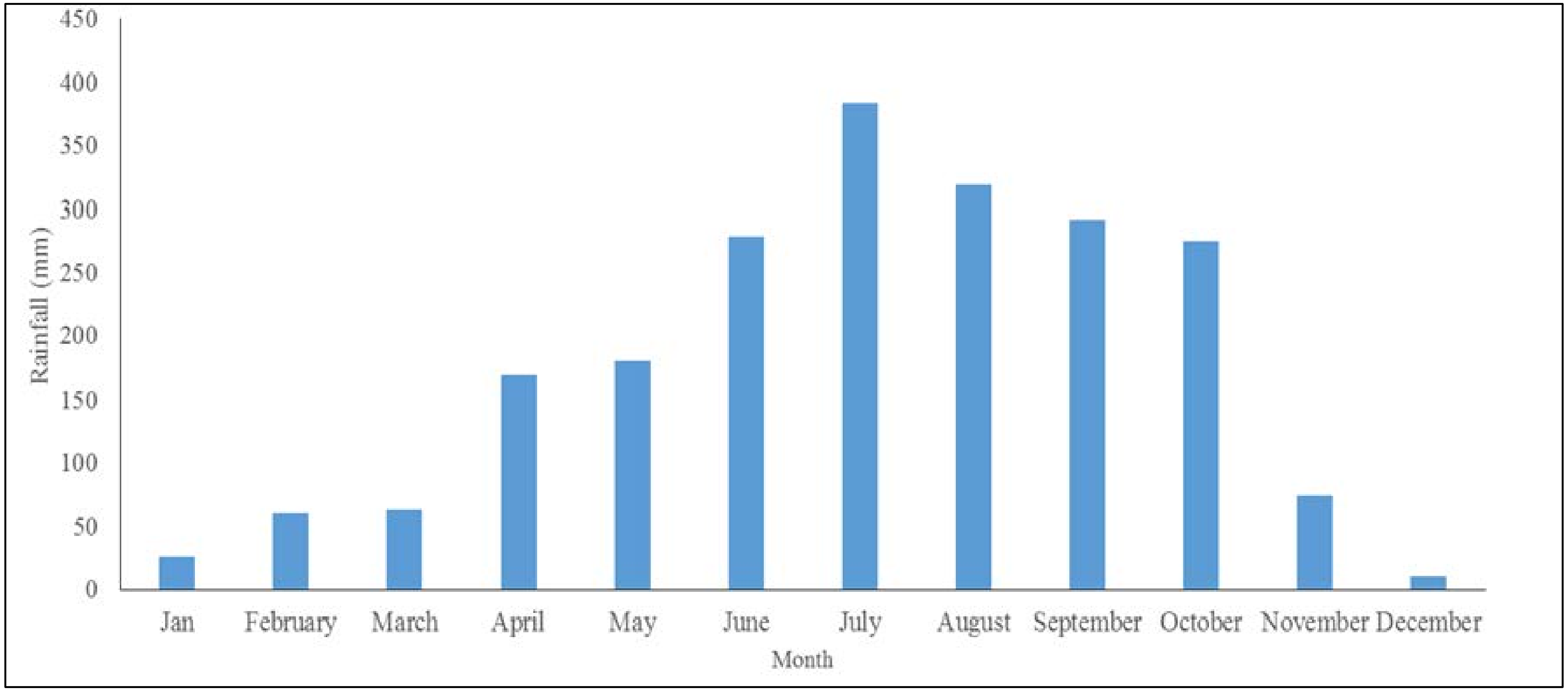

Fig 3.15: Monthly 6-year mean (2008-2013) rainfall (mm) across the SE Geopolitical zone

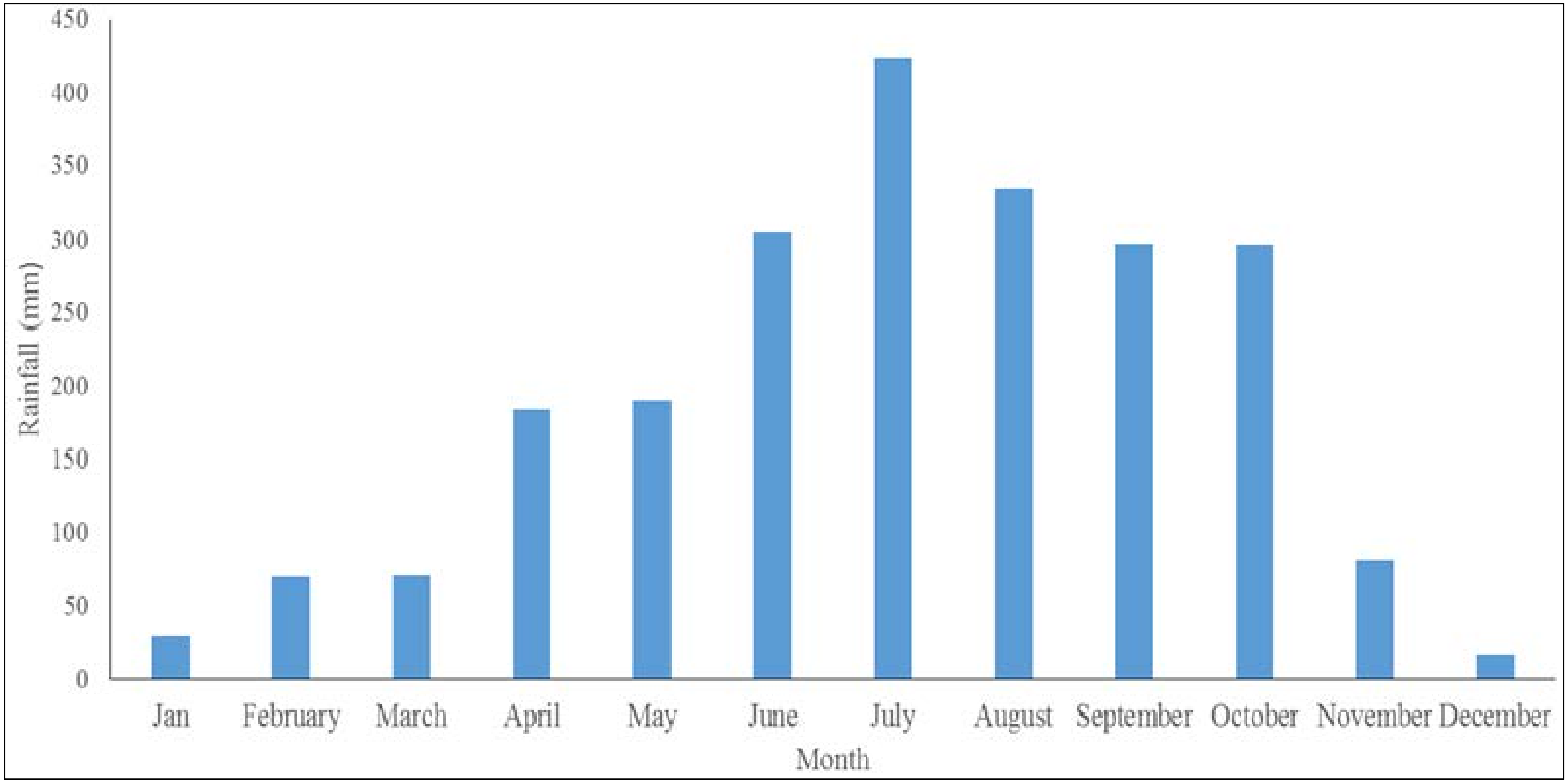

Fig 3.16: Monthly 6-year mean (2008-2013) rainfall (mm) across the SS Geopolitical zone.

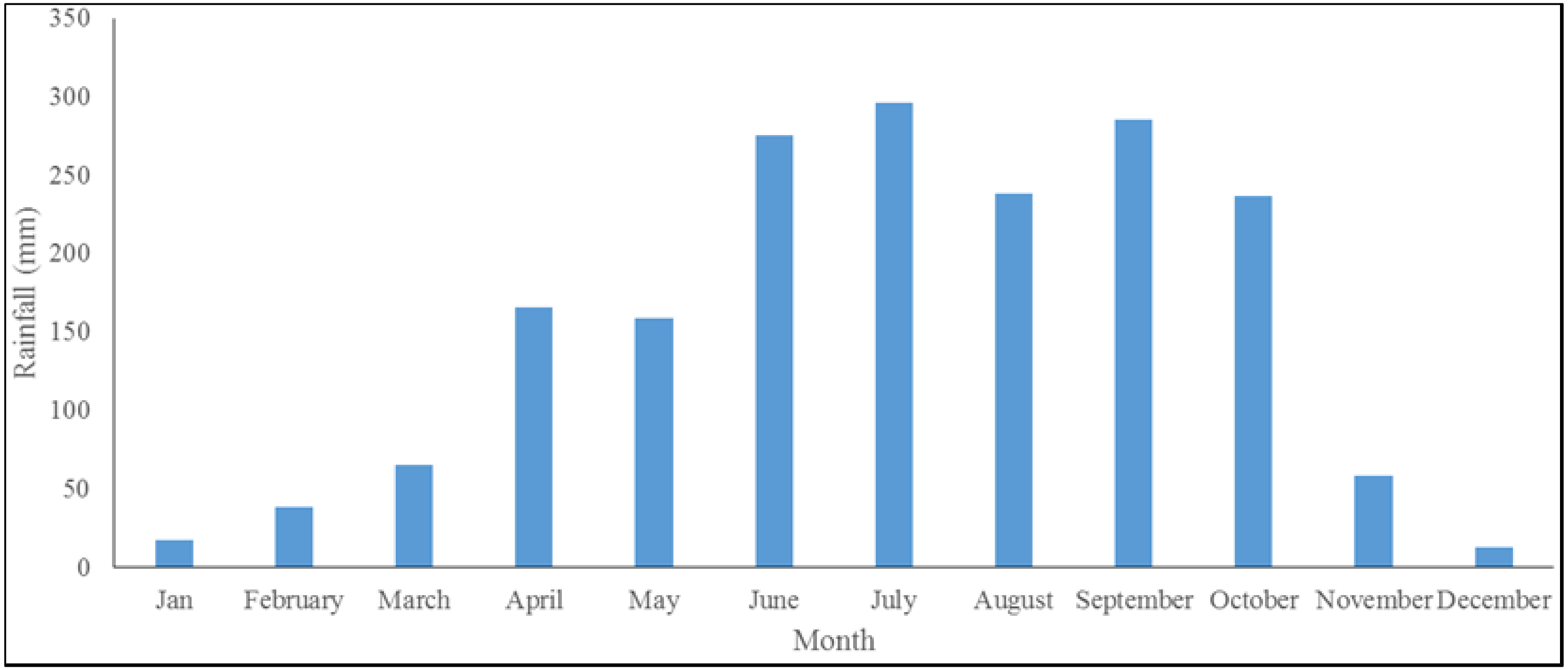

Fig 3.17: Monthly 6-year mean (2008-2013) rainfall (mm) across the SW Geopolitical zone

3.7.7 Temperature requirements of the four selected crop species

Miscanthus

Hager *et al.* (2014) identified that the tropical region of Northern China with maximum temperature was favourable for growing C4 miscanthus species like *M. sinensis* and *M. sacchariflorus*. According to Mitchell (2013) it was evident that the SE zone can support the growth of C4 species, since the study stated that the productivity of miscanthus species decreases at limiting temperature of 12 to 14^{o}C but rapid growth is achieved at optimum temperatures of 25 to 28^{o}C, which is in line with the temperature ranges obtained in this zone.

The observed minimum temperature (21^{o}C) in the NC zone was much higher than the minimum threshold temperature at 6^{o}C reported by Caslin *et al.* (2010) for the growing of *Miscanthus x giganteus*. Imperatively, this suggestion implied that *Miscanthus x giganteus* will thrive across most zones from February to May when the highest temperatures are recorded, e.g. 29 to 31^{o}C. Similarly, Kandel *et al.*, (2013) also stated that the growth and yield of the species can be achieved within an optimum temperature range of 20 to 30^{o}C, however, a rapid decrease in growth and yield of the species is likely to occur at high limiting temperature of 37.6^{o}C.

The temperature range of the NE zone will not only favour *Miscanthus x giganteus* but all the C3 and C4 species including alfalfa, switchgrass and elephant grass since the minimum limiting temperature for growing the crops is 10^{o}C.

Switchgrass

Hashemi and Sadeghpour (2013) indicated the optimum temperature range of 27 to 30°C for the growth and development of switchgrass cultivars. This was further supported by Salon and Miller (2012) that the warm season grasses can favourably grow at temperatures between 18°C and 35°C. According to Rahman *et al.*, (2014) the germination and growth of switchgrass is most achievable above a minimum temperature of 20^{o}C. Parrish and Fike (2005) also reported that the growth of switchgrass is tied to temperature distribution across a location. The study demonstrated that though germination of warm-seasons crop can be achieved at an optimum maximum temperature of 35◦C and 32◦C, maximum growth can be attained with minimum and maximum temperatures of 20 and 30◦C.

Alfalfa

Nyoka *et al.,* (2007) reported that the germination of C3 species are most favourable at minimum and maximum temperatures between 10 to 25°C. The same author reported that alfalfa can successfully germinate between minimum and maximum temperatures of 15°C to 30°C. Deng *et al.,* (2014) also noted that the optimum temperature for growing alfalfa is 15 to 20°C. Based on these reports, it is clear that though alfalfa can grow in Northern Nigeria but maximum growth and yield of the plant is likely to in the SE due to the favourable climate. Alternatively, alfalfa may perform better than the C4 species in the South whereas in the North it is likely to be outperformed by the three C4 crop species evaluated in this study.

Elephant grass

Rahman *et al.* (2014) highlighted that the most suitable temperatures for growing *Miscanthus x giganteus* in the tropics is between minimum and maximum temperature of 15 to 35°C. This was therefore enough evidence to support that the entire SS zone has optimal temperatures suitable not only for the production and growth of the C4 *Miscanthus x giganteus,* (Rahman *et al.,* 2014), elephant grass (Adjolohoun *et al.,* 2008; Adjolohoun, 2008) and switchgrass but also favourable for the growth of the C3 species. Further evidence to support this claim is a similar study within this zone (River state-Nigeria), which estimated that maximum growth for elephant grass can be achieved at an optimal temperature of 27°C (Obok *et al.*, 2012). Also in Ghana, another study pointed out that the Tmin and Tmax requirements for growing elephant grass are 21^{o}C and 34.0^{o} C respectively (Ansah *et al.*, 2010).

Elephant grass production has been identified to thrive at Tmin and Tmax of 25 – 30^{o}C during the daytime or Tmin and Tmax of 16 – 21^{o}C during the night. The study indicated that higher temperature at 25 – 30^{o}C stimulated rapid development of the plant. The study further concluded that low temperature has great limitation to the effective growth of the crop (Ferraris, 1978).

Also, according to the result of a field trial experiment carried out at the Brawley Research Centre in California, it was discovered that elephant grass can be successfully established at a mean annual temperature of 23^{o}C during a mild winter and a daily Tmax greater, or equal to 38^{o}C in a hot, dry summers (Wang *et al.*, 2002).

Another study in the South-Eastern USA (Florida), showed a quicker establishment and high biomass yields of elephant grass at daily average maximum and minimum temperatures of 27°C and 12.4°C (Erickson *et al.*, 2012).

There is little variation in annual temperature across the zones, therefore, it can be concluded that the six zones are actually suitable for growing all of the four selected crop species. The claim is based on the similarity between the results and the optimal temperature of the 4 crop species. Against this background, the NC zone had average annual temperature of ranging from 24.4 to 28^{o}C, NE with 25.2 to 28^{o}C and NW zone, 21 to 27.4^{o}C. In the South, the SE zone was observed to have slight decrease in mean average annual temperature, with the Tmin and Tmax of 21 to 25^{o}C, SS zone had 25 to 27.3^{o}C while the SW zone had similar temperature range at 27 to 27.3^{o}C (Fig 3.10). Generally, the country was observed to experience suitable climatic condition all year round to support successful establishment of the selected perennial energy crops (Fig 3.10).

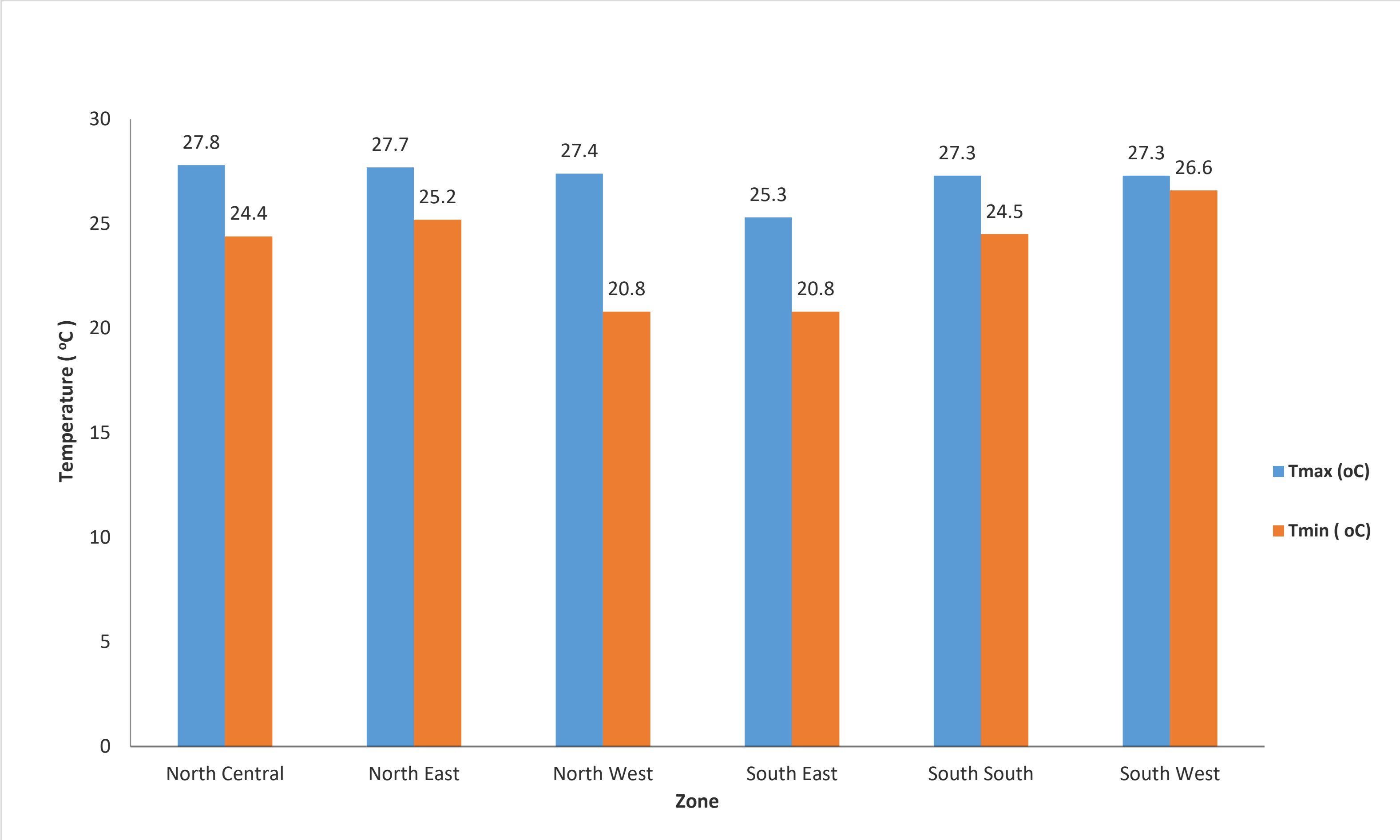

Figure 3.18: Variation in maximum and minimum mean temperature distribution across the 6 Geopolitical zones of Nigeria

3.8 Processing of Digital Elevation Model (DEM)

Step 1: The DEM data were imported into ArcGIS and mosaic of the raster sheets done by adding the input raster data to the Arc map using Arc toolbox.

Step 2: The DEM data (Fig 3.7) was projected from the WGS84 to AAEA. The cell sizes (x, y) were resampled to $300m^2$, to ensure the same cell size as for all the other data. The essence of changing the coordinate systems as well as re-sampling to the same size was to ensure that each layer file would overlay correctly with each other.

Step 3: The Data management tool was used to add and clip out input dataset from the output extent (Fig 3.7). The input feature was also maintained to ensure appropriate clipping of each state

3.8.1 Derivation and processing of slope map

The z factor was changed from 1 to 0.00000912 in order to enable appropriate calculation. This is because, if the x, y units and z units are of the same measurement, then the z factor becomes 1 but if x, y units of the input raster surface are different from the z unit then an appropriate factor (0.00000912) was applied to ensure that an accurate result is achieved. Since all necessary processing was already carried out in DEM, Raster clip was used to clip out all the 36 states and FCT from the slope map.

3.8.2 Classification and evaluation of slope

Gentle slopes with $<5^o$ are best for both the C3 and C4 species, while steep slopes $>12^o$ were indicated to be unsuitable for all the species since they limit the use of specialized management practices, e.g. machinery required for growing the crop species (Fig 3.11 and Orloff, 2007).

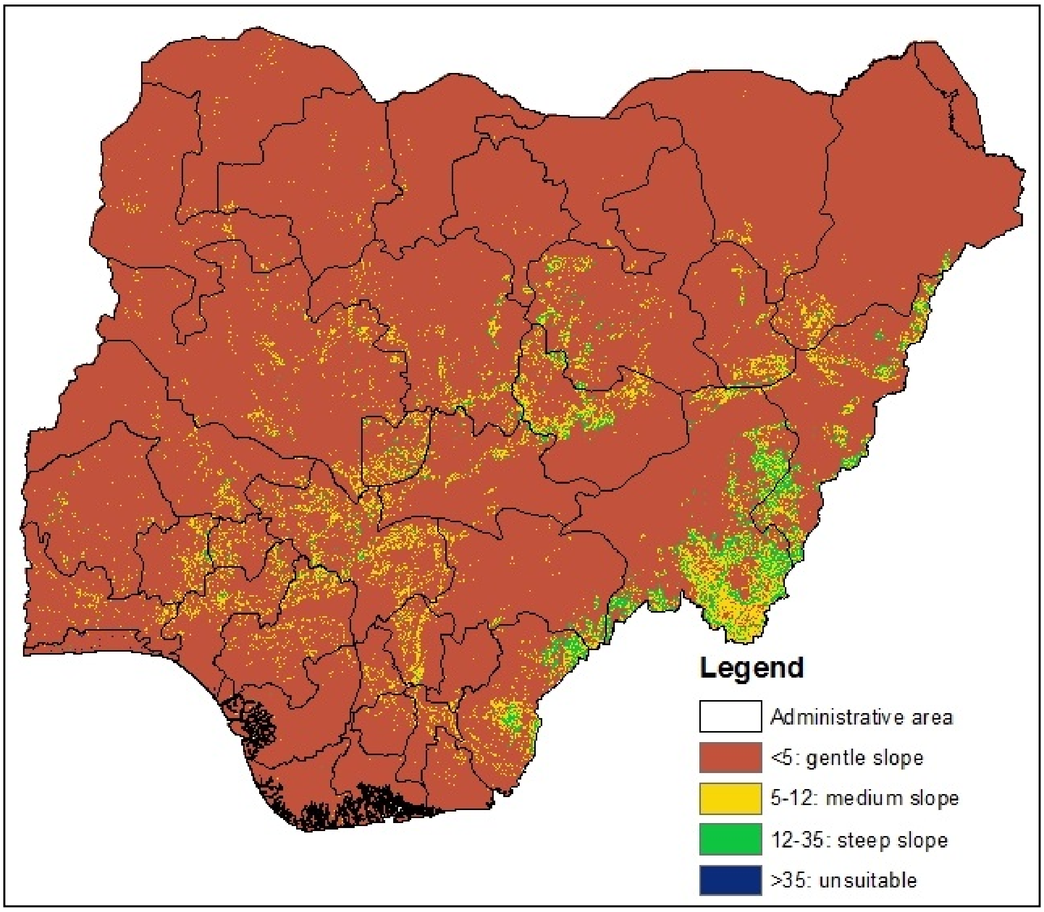

Figure 3.19: Slope map of Nigeria derived from the Digital Elevation Model (DEM)-Shuttle Radar Topography Mission (SRTM) (Global), using the country's administrative area to clip out the resampled output data.

3.9 Processing of soil data

The soil data of Nigeria comprising of soil pH (top soil) and organic carbon (top and subsoil) in % was obtained in person from the National Programme for Food Security (NPFS-FAO, Nigeria). The pictorial soil map was converted to digital format and the spatial reference projected to the AAEA system. The four soil characters in the layer file were converted to shape files and raster formats. The conversion was carried out via Polygon to Raster tool by importing input features into Arc map. The output features were reclassified and the cell sizes resampled from 4500m^2 to 300m^2. Resampling the cell sizes to 300m^2 was done to assign the same cell sizes to all datasets and the conversion to raster file basically to enable suitability analysis to be carried out using raster calculator. The soil features were reclassified according to FAO suitability framework to identify suitable and unsuitable areas for each of the selected species (Fig 3.12 and 3.13).

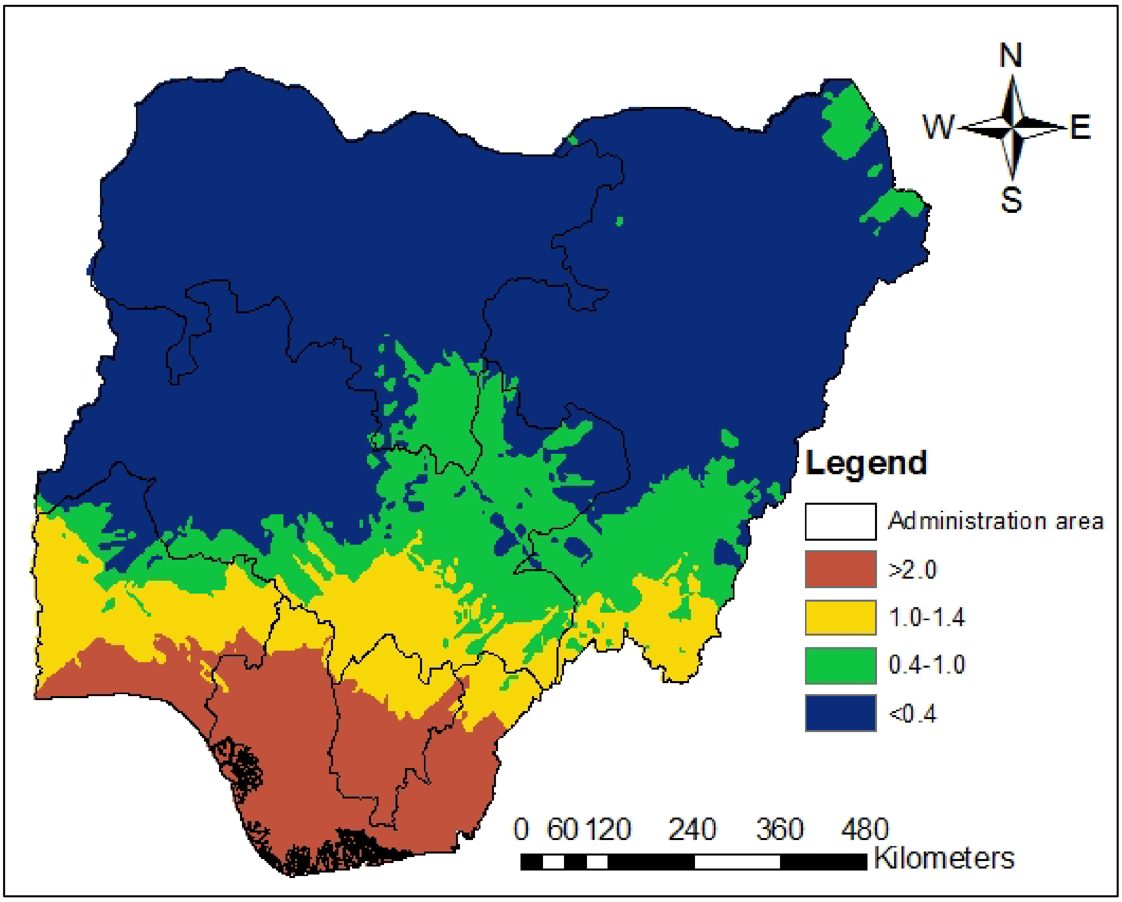

Figure 3.20: A rasterized soil organic matter content (SOM) across the six Geopolitical zones of Nigeria, collected from the National Programme for Food Security (NPFS-FAO).

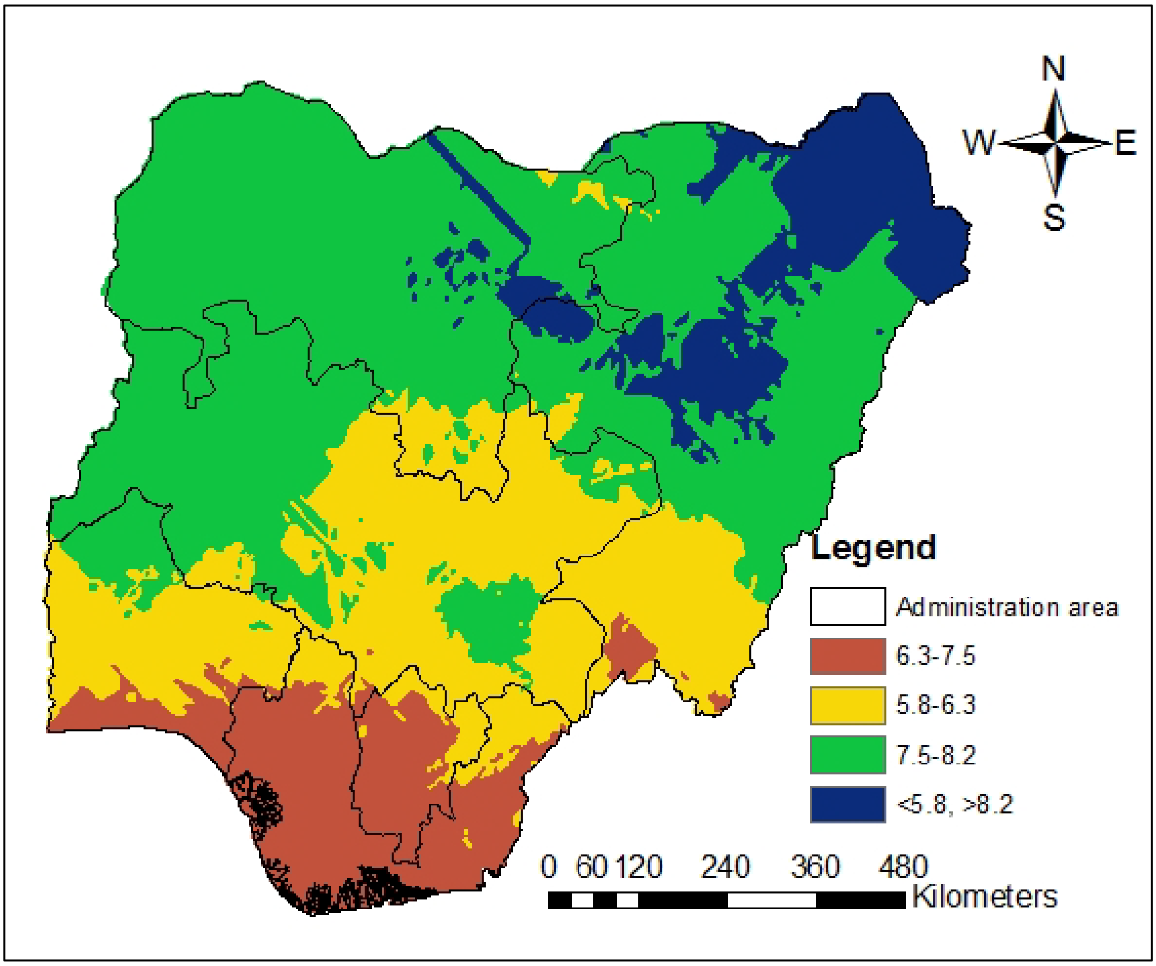

Figure 3.21: A rasterized map of soil pH, generated and collected from the National Programme for Food Security (NPFS-FAO) Nigeria.

Chapter 4: Literature based information to support factor weighting

This chapter presents the essential information from the literature on the production variables of selected energy crops. The information was employed in the subsequent chapter (5) to allow factor weighting based on their relative importance to optimal growth conditions. The process was enabled by z integrating Multi-Criteria Decision Method (MCDM) with Geographical Information Systems (GIS) software

4.1 Evaluation of literature information to support the weighting allocation

In order to evaluate the productive potential of each species, factor weights were employed to express the importance of the derived parameters to compare each criteria to another and establish the preference or most relevant factor(s) that will be required and determine the suitability levels for constructing criteria maps (Kihoro *et al.*, 2013).

Although most studies apply a quantitative approach to interview and gather expert opinions in order to calculate relative importance of the factors and assign weights to each (Tienwong *et al.*, 2009). This study has been designed to establish and assign criteria weights to the potential productive factors of the selected energy crops based on scientific reports in the literature. This approach has previously been used in India to identify sustainable manufacturing practices for electrical panel production (Gupta *et al.*, 2015).

Further studies have used a literature-based approach to identify the most important factors to enable them to determine criteria weights and evaluate land suitability (Eterovic and Özgül, 2012). Ahmadi (2014) could not identify any study in the literature which applied AHP for ranking critical factors of Healthcare Information Systems (HIS), rather the author was able to rank the critical factors of HIS using AHP in order to calculate the relative weights of various attributes. In Kenya, Kihoro *et al.,* (2013) also employed literature-based information to identify climate conditions to determine land suitability for rice production.

4.2 Land suitability analysis

Land suitability is generally defined as the characteristic of possessing the preferred land requirements for a particular purpose (Estoque, 2011). It is mostly applied in land resources planning across the globe using both soil, topography, vegetation (Olaniyi *et al.*, 2015) and climate datasets (Kihoro *et al.,* 2013).

Land suitability analysis is a process which employs a GIS-based approach to identify an appropriate land area for use in agriculture, forestry, urban development (Estoque, 2011) or the health care sectors.

Land suitability evaluation is being employed to address and predict specific issues related to crop productivity. In order to achieve the sustainable productivity of crops, several matching land characteristics are applied to meet a particular purpose (Olaniyi *et al.*, 2015). According to Akıncı *et al.* (2013) the major reasons for using basic parameters like soil, land use and topography is because of the adequacy for predicting areas where vegetative production can be situated. The second reason is basically as a result of the fact that such a study does not require the prediction and allocation of specific crop species.

However, in this study several other parameters like temperature, rainfall, pH and soil OM are included in order to meet the requirements for each specific crop species.

These land characteristics and crop requirements; land cover, slope, temperature, rainfall, pH and soil OM were selected based on expert's knowledge and information from the literature Ayehu and Besufekad (2015) to enable estimation of criteria weights. The essence of this estimation was to determine the percentage influence of each factor (Olaniyi *et al.*, 2015).

4.3 Selection of factors and suitability levels

According to the FAO land suitability classification, four suitability levels for each factor were ranked to include the following; Highly suitable (S1), Moderately suitable (S2), Marginally suitable (S3) and Not suitable (N) (Ayehu and Besufekad,2015).

Climate: Climatic conditions have a tremendous effect on the growth, development and yield. Temperature and rainfall are selected in this study based on the contribution to the potential productivity of the C3 and C4 crop species. The fact that the selected herbaceous perennial species are tropical and sub-tropical species means they are likely to adapt fairly well to the high temperature and rainfall zones of Nigeria with annual minimum and maximum temperature of $24^{o}C$- $32.49^{o}C$ respectively and annual rainfall varying between 1614 and 2136 mm (Ogbuene, 2010). According to Abdullahi *et al.* (2013) who evaluated a switchgrass trial in the extreme North of Nigeria and showed that the selected C4 herbaceous perennial species can survive well in a low rainfall range of 552 to 600mm. Therefore, climate is considered as the key factor since switchgrass survived under very low rainfall conditions in the extreme North, while a more bountiful growth and yield could be achieved in Southern Nigeria with higher temperatures $24^{o}C$- $32.49^{o}C$ and rainfall of 1614 to 2136mm (Ogbuene, 2010). Kristen (2008) also noted that C3 grasses can grow below daily maximum temperature of 25°C.

Soil: Soil is one of the major factors that plays a major role in crop production (Baniya, 2008) since it provides necessary nutrients for the growth and development of crop species, and is therefore recommended as an essential factor in determining land suitability (Ayehu and Besufekad, 2015). Though most C3 and C4 can actually grow on a wide variety of soil types, either in shallow rocky areas or wet areas, so soil type is not always a preferred factor for land suitability evaluation (Lewandoski *et al.*, 2003). In this study, soil pH and organic matter (OM) were also adopted as essential criteria for suitability analysis, since plants require soil pH at different levels for proper growth, while organic matter at the same hand enhances the nutrient and water holding capacity to improve the productivity of plants (Ayehu and Besufekad, 2015). A study in Nigeria (Ayorinde *et al.*, 2015) also used similar factors: organic matter, pH, slope, rainfall and temperature to carry out crop suitability evaluation. These factors according to (Ayorinde *et al.*, 2015) were established from expert's opinion and information from the literature. The criteria weights were rated based on their importance to achieving optimal growth conditions (Emenike *et al.*, 2018).

Slope: The development of soil structure is directly related to the topographical nature of the area. This implies that the thickness of soil decreases with increasing slope level, while the increasing level of slope determines erosion control resulting in potential deficiencies in soil fertility, a steep slope of about 30% affects agricultural production due to the inability to use most machinery (Akıncı *et al.*, 2013). Steep slopes discourage the use of an intensive tillage system (moulboard plough), and for perennial crops ploughing is not carried out annually, but once per crop establishment (Clifton-Brown *et al.*, 2007). while at above 11% slope level more intensive cropping or tillage system leads to excessive erosion levels which in turn threatens the long-term productivity of the soil resource (Richard *et al*, 2009).

Table 4.1: Literature derived information for switchgrass *(Panicum virgatum)*

Location	Max. temp (ºC)	Min. temp (ºC)	Rainfall (mm)	Elevation (m)	SOC (%)	pH	Yield (t/ha)	Unsuitable Factor	Important Factor	Author Year
Nigeria	27-40	18	552-600	242	14-17.6	5.8-6.6	-	40ºC	Water (rain/irrigation)	Abdullahi *et al.*, 2013
USA	20-30	10	400-1200	-	-	-	10.9		Water (precipitation)	Wang *et al.*, 2002
USA	23 – 38	15-23		-	-	-	-	≥ 37.6 ºC	Temp.	Kandel *et al.*, 2013
USA	20-30	≤ 20	High	-	-	-	-	< 20 ºC	Water (precipitation)	Mitchell *et al.*, 2014
USA	25-30	20	High	-	-	-	16.4	≤ 20 ºC	Water/temperature	Butler *et al.*, 2014
Greece	30-35	15-22	50-100 350	107.5	-	High	-	Insufficient water	Water (rain/irrigation)	Giannoulis *et al.*, 2009
Massach., USA	27-30	20	High	-	-	-	-	Insufficient water, pH <4 or > 8	Water (rainfall)	Hashemi and Sadeghpour, 2013
IOWA, USA	-	-		-	-	6.7- 6.9		<25 or >35	-	Brummer *et al.*, 2000
Northern, USA	25-35	-		-		5.0-8.0.	-	-	-	Hanson and Johnson, 2005

Florida, USA	25		300-1500						Water	Hartman *et al.*, *2011*
Nebraska, USA	-	-	-	-	-	-	-	-	Water (irrigation)	Salon & Miller, 2012
Dakota, USA	-	-	-	-	High	-	-	-	Water	Newman, 2008
Virginia, USA	27-30	20	High	-	-	-	-	-	Water	Sanderson *et al.*, 2012
Great, USA	>20	10-15	High	-	-	-	-	-	Water	Nyoka *et al.*, 2007
Mississippi, USA	27-30	-	High	-	-	>5.0 and <8.0	-	-	Water	Wolf and Fiske, 2009
Darkota-USA	-	-	High	-	-	-	-	-	Water	Lewis *et al.*, 2014
Kansas, USA			High		High	4.8-7 5.5-6			Water	Arias *et al.*, 2009
Southern, USA	-	-	-	-	-	-	-	-	Water/ temperature	Thapa, *2012*
USA.	26 °C	1.2	820	-	-	-	-	-	Water	Hartman and Nippert, 2013
GP, USA	26°C	14	> 600	-	-	-	-	-	Water (precipitation)	Wullschleger *et al.*, 2010
Northern, Italy		10-15	< 700	> 750 m		< 5.0 and > 8.5			Water & temperature	Fiorese & Guariso, 2010
Florida, USA	25 to 35	10				3.7	15		Water & about 32◦C	Parrish and Fike, 2005

Table 4.2: Derived factors from the literature for miscanthus ***(Miscanthus x giganteus)***

Location	Max. temp (ºC)	Min. temp (ºC)	Rainfall (mm)	SOM (%)	pH	Slope (°)	Elevation (m)	Yield (t/ha)	Unsuitable Factor	Important Factor	Author Year
Europe, Portugal	17.5	10-12	500-1000			-	-	30	-	-	Lewandowski *et al.*, 2000
England	>6	6		High	5.5-7.5			12-16	-	Temperature and water	Nixon and Bullard, 2001
Iowa, USA	20-25	10 to 15	> 500	-	-			15–20	Insufficient water (<500)	Water availability	Widholm *et al.*, 2010
UK	-	-	<100->300		<5-10				15% slope	Soil water, temperature	Richter *et al.*, 2016
Washington, USA	>10	10	>762	High	5.5-7.5			24-30	pH >8	Water availability	Williams and Douglas, 2011
Northern, Italy	>15	10	700	High	5.0-8.5			-	<10ºC, <700	water, temperature	Fiorese and Guariso, 2010
Northern Ireland	>15.5	15.5	High	High	5.5 - 7.5.			10 -13			Caslin *et al.*, 2010
Illinois, USA	28	10	>300	High	6.5-8.0	-					Bowen & Hollinger 2004

Table 4.3: Important factors derived from the literature for Alfalfa

Location	Maximum temp (ºC)	Minimum temp (ºC)	Rainfall (mm)	SOM (%)	pH	Elevation (m)	Slope (°)	Yield (t/ha)	Unsuitable Factor	Important Factor	Author & Year
Southern Great Plains, USA.	25-35	10-20	-	-	-	-		-	-	Temperature	Butler *et al.. 2014.*
Northern, USA	-	-	-	-	6.5-6.8			-	-	-	Undersander *et al.*, 2011
California, USA	20-24	18	-	-	-			-	1.7 or >40ºC	-	Mueller and Teuber, 2007
Montana, USA	-	-	-	-	6.5-7.0			-	-	-	Dixon and Kincheloe, 2005
California, USA.	24	30-38	203-457, 1,295	-	-			-	41ºC	-	Putnam *et al.*, 2007
Northwestern, China.	20.7	9.2	253.9-259.4	0.8	-			-	-	-	Li *et al.*, 2007
Qazvin province, Iran	-	14.1	-	-	-			-	sufficient moisture	available water	Taati, *et al.*, 2015
			1, 220		5.8-6.3 ideal, 7.5-8.2 marginal		0-5 gentle, 12 slightly		Insufficient water, pH >8.2, slope >12	Adequate water	Orloff, 2007

Table 4.3: Important factors derived from the literature for Alfalfa (continued)

Location	Maximum temp (ºC)	Minimum temp (ºC)	Rainfall (mm)	SOM (%)	pH	Elevation (m)	Slope (°)	Yield (t/ha)	Unsuitable Factor	Important Factor	Author & Year	Location
East Azarbaijan, Iran	40	-	302.8	-	-				-	-	-	Jafarzadeh *et al*., 2008
Mongolia, China.	35	25	-	-	8.1				-	-	-	Xu *et al*., 2016
Northern China	15-20	6	400-600	0.18-8.55	7.3-8.1			15	-	<6ºC, pH,	Temperature	Deng *et al.*, 2014
Eastern Desert, Egypt	20-35	-	> 80	-	7.6-7.3			0-2	-	-	-	Belal *et al.*, 2015
Arid Region, Iran.	32-40	15-20	30-90	-	7.0-7.8			-	-	< 10 and > 40ºC. < 20 and > 90mm	20-28ºC	Yaghmaeian Mahabadi *et al*., 2012.
Southern U.S.A	-	15.6	508	-	6.8 to 7.0			-	-	-	Water and pH	Haby *et al.*, 1997
North China.	>10	10	-	-	-			-	-	-	Water and temperature > or = 10oC	Chang *et al.*, 2012

Table 4.4: Literature derived information for Elephant grass *(Pennisetum Purpureum S.)*

Location	Maximum temp (ºC)	Minimum temp (ºC)	Rainfall (mm)	SOM (%)	pH	Slope (°)	Elevation (m)	Yield (t/ha)	Unsuitable Factor	Important Factor	Author & Year
Georgia, USA	30–35	10	750- 2500	High	High	-	2100	45	Insufficient temperature	Optimum temperature	Singh *et al*, 2013
South China	-	-	-	3.9	6.1	-		-	-	-	Zhang *et al*, 2010
California, USA	38	23	700	-	-	-	-	-	-	Temperature	Wang *et al*, 2002
Queensland, Australia.	25-30	16-21	-	-	-	-	-	-	Low temperature	Temperature	Ferraris, 1978
Florida, USA	27.2	12.4	850-1150	-	-	-	-	35 to 40 t	Insufficient water availability.	Temperature	Erikson *et al*, 2012
Calabar, Nigeria	26.8	14.3	0.226 RH:72-90	14.9g/kg= ~1.5%	6.6,	-	-	-	-	-	Obok *et al*, 2012
Bayelsa, Nigeria	-	-	-	-	5.6–6	-	-	-	-	-	Ohimain *et al*, 2014
Thailand	-	-	> 1,000	-	4.5-8.0	-	-	-	-	-	Pratumwan *et al*., 2015.
Port Harcourt, Nigeria	27	-	2700	-	-	-	-	-	-	Temperature	Ayotamuno *et al*., 2006
Kumasi, Ghana	34oC	27	1194	-	-	-	-	85.4	-	Temperature	Ansah *et al*, 2010

Table 4.5: Suitability ranges for the C4 species; Switchgrass (A), *Miscanthus x giganteus* (B), Elephant grass (C) and the C3 species; Alfalfa (D).

Parameters	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Not suitable (N)
A. Switchgrass				
Temperature (ºC)	25-35	15-20; 36-40	10-15	<10>40
Rainfall (mm)	800-1600	400-800	100-400	<100
Soil pH	5.0-6.0	6.0-8.0	8.0-8.3	<5.0, >8.3
Soil organic matter (%)	>2.0	1.4-2.0	1.0-1.4	<1.0
Slope (º)	< 5.0	5.0-8.0	8.0	12
Elevation (m)	<300	300-700	700-1500	>1500
B. *Miscanthus x giganteus*				
Temperature (ºC)	25-33	15-25	10-15	>10>33
Rainfall (mm)	>1000	700-1000	400-700	<400
Soil pH	5.5-6.5	6.5-7.5	7.5-8.0	<5.5, >8.0
Soil organic matter (%)	>2.5	2.0-2.5	1.5-2.0	<1.5
Slope (º)	<5	5-7	7-10	>10
Elevation (m)	<450	450-100	1000-210	>2100
C. Elephant grass				
Temperature (ºC)	25-30	20-25	10-20	< 10>30
Rainfall (mm)	>1000	700-1000	100-700	< 100
Soil pH	5.6-6.0	6.0-7.0; 5.0;5.5	7.0-8.0	<5.6, >8.0
Soil organic matter (%)	> 2.5	2.0-2.5	0.5-2.0	< 0.5
Slope (º)	1-5	5-7	7-10	>10
Temperature (ºC)	25-30	20-25	10-20	< 10>30
Elevation (m)	< 500	500 -2100	2100-4000	>4000
D. Alfalfa				
Temperature (ºC)	20-30	10-20	5-10	<5; >30
Rainfall (mm)	>1000	500-1000	100-500	<100
Soil pH	6.2-6.8	6.8-7.3;	7.3-8.1	<6.2, >8.1
Soil organic matter (%)	>5.0	3.0-5.0	1.0-3.0	<1.0
Slope (º)	0-3	3-4	5-15	>15
Elevation (m)	<1000	1000-1500	1500-2300	>2300

Source: (Table 4.1-4.4; Appendix 54-57). Based on the information derived from the various literature sources reviewed, we have been able to establish the land use suitability classes for all the parameters required for the 4 bioenergy species (Table 6.1). This information allows evaluation of priority weights to determine the importance of criteria and also carry out the land suitability of the selected C3 and C4 species (i.e. alfalfa, elephant grass, *Miscanthus x giganteus* and switchgrass) in subsequent chapters.

Chapter Five: Weighting of Land Suitability Factors

This chapter provides the general framework and preferred approach to carry out the criteria weighting prior to suitability analysis. It presents spatial information which is incorporated with the GIS-based multi-criteria decision making method (i.e. Analytical Hierarchy Process).

5.1 An overview of Multi-criteria decision-making (MCDM)

Multi-Criteria Decision Making (MCDM) is an operational research model used in addressing real world complex decision making problems (Roszkowska, 2013). It is a generic method which enables decision making process based on individual preferences (Løken, 2007). The importance and usefulness of MCDM has been widely recognised particularly in recent times due to the emergence of computer technologies, which provide vital information for decision making process. MCDM combines and transforms spatial information and problems involving biophysical, socio-economic, site location and environmental systems (San Cristóbal, 2012) to make valuable judgments, such as for example, site selection for housing development (Meng *et al.*, 2011).

According to Roszkowska (2013) the formation of a MCDM problem with m decision alternatives and n decision criteria can be presented as $A_1, A_2, \ldots, A_m$ and $C_1, C_2, \ldots, C_n$, respectively, where the alternative scores in regards to the criteria are known to the decision maker.

The weight vector $w = [w_1, w_2, \ldots, w_n]$, satisfies the expression that $w_1 + w_2 + \cdots w_n = 1$

Since $i = 1, 2, \ldots, m$ *and* $1, 2 \ldots n = j$, therefore the weight and decision criteria follow

$W_j, C_j \geq 0$ and the decision matrix is $D = (X_{ij})_{mxn}$, where X_{ij} denotes the performance value of alternative A_i in terms of criterion C_j.

In a general context, MCDM problems with *m* alternatives and *n* criteria are given by ***A*** $=\{A_1 A_{2,\ldots,} A_m\}$ and $C = \{C_1, C_2, \ldots, C_n\}$ respectively. Basically, this assumption is expressed by $D = (X_{ij})_{mxn}$ and $w = [w_1, w_2, \ldots w_n]$.

There are several types of MCDM that use both alternatives and criteria to carry out the decision process. These include: Simple Addictive Weighting (Yano *et al., 2009*), the Technique for Order Preferences by Similarity to the Ideal Solution (TOPSIS) (Roszkowska, 2011) and the Analytic Hierarchy Process (AHP) (Satty, 1987). These have been acknowledged by researchers particularly for use in solving complex problems related to multiple-criteria and systematic properties (Triantaphyllou and Mann, 1995). The SAW approach is regarded as the simplest form of the MCDM since it uses a simple aggregation procedure (Stanujkić *et al.*, 2013). The major disadvantage of SAW is that the yield estimates of the results does not always synchronize with the real situation, in the sense that the value of each criterion may have significant difference from other criteria (Velasquez and Hester, 2013). Furthermore, although SAW is extremely simple to use in diverse areas, like water, business and financial management, the author (Velasquez and Hester, 2013) indicated that SAW has limited applications in solving problems (ibid), since the results does not present the real fact.

According to Velasquez and Hester (2013) the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is another logical approach that can be used to confirm the proposed results of other MCDM methods. Though the method uses a programmable process to estimate decision problems, the major constraint of this technique is that its use of the Euclidean Distance does not consider the correlation of attributes. The main disadvantage of this method is the difficulty in factor weighting and estimation of consistency measures.

5.2 The Analytical Hierarchy Process

5.2.1. Justification and application of AHP for carrying out a decision process

The Analytical Hierarchy Process (AHP) is one of the multi-criteria decision-making approaches developed by T. L. Saaty between 1971 and 1975, which was introduced to deal with complex decision making problems (Triantaphyllou *et al.,* 1995). Saaty (2008) defined AHP as a 'theory of measurement' performed using pairwise comparisons which relies on experts judgements in order to derive priority scales. The main concept of AHP is to pairwise compare all criteria and make important decisions, such as resource planning and allocation (Saaty, 1987). This can be done by structuring selected criteria into a hierarchy (Gupta *et al.,* 2015) to carry out a Pairwise Comparison Matrix (PWCM) in order to compare alternatives and determine criteria weights (Velasquez and Hester, 2013).

According to Velasquez and Hester (2013) one of the major advantages of the AHP is its ease of use. It is the most widely used MCDM approach which considers both the tangible and intangible factors to reduce the complexity of decision problems, by comparing different attributes (Eterovic and Özgül, 2012). The use of pairwise comparison enables decision makers to easily weight the coefficients and compare various alternatives. Another advantage of AHP that made it the best choice for this study, is that the scales of intensity of importance for the criteria can be adjusted to accommodate decision processes based on their hierarchical structure (Velasquez and Hester, 2013).

A further advantage of AHP is its applicability to specify the relationship between large numbers of criteria (Olaniyi *et al*., 2015). The interdependency between the criteria and alternatives is the major factor that affects the process due to the approach of pairwise comparisons and the inconsistent judgment of criteria (Velasquez and Hester, 2013). The managerial level deals with the goals as well as choosing the final optimal alternative, while the engineering level defines the alternatives and points out the consequences of choosing various criteria (Velasquez and Hester, 2013).

The Analytical Hierarchy Process is widely accepted within the literature (Meng *et al*., 2011) and considered by many as a reliable approach of the Multi-Criteria Decision Making method for land suitability analysis (Ayehu and Besufekad, 2015) which is one of the research objectives of this study. For example, a study in Ethiopia, applied the GIS-based MCDM method and soil, climatic and topography criteria to identify highly and moderately permissible locations suitable for rice production in the West Central highlands of the Amhara region (Ayehu and Besufekad, 2015). The method involves assigning values to each criterion based on their relative importance or preferences to one another. This process generally involves expert opinion, indigenous knowledge, field surveys and comparison of existing land use with location specific characteristics (Olaniyi *et al.*, 2015).

In Canada, Meng *et al*. (2011) employed GIS-based MCDM to carry out site suitability analysis. This technique was also employed by Kihoro *et al*. (2013) to identify agricultural land suitability in Turkey. The approach provides desired solutions to increasing complex management problems (San Cristóbal, 2012), such as forest, agriculture and energy crop production processes. AHP had also been applied to evaluate and allocate crops to the most suitable locations (Vaidya and Kumar, 2006).

5.2.2 The basic principles of the Analytical Hierarchy Process

The subsequent steps indicated by Saaty (1987 and 2008), as well as Janic and Reggiani (2002) were employed in this study in order to successfully apply the AHP method and carry out the necessary evaluation. The steps include: decomposition of the problem, making of comparative judgments and synthesis of priorities.

Decomposition of problem. It deals with the hierarchical representation of the overall goal and decision alternatives of the problem.

*Comparative judgement**.*** This includes the formulation of the pairwise comparison matrices. The comparative matrices are further categorised into two different ways: levels where the alternatives are compared based on the various criteria, and a process whereby the criteria are compared based on the overall goal. According to Nekooee *et al.* (2011) the overall goal of the problem is usually classified as Level 1. The hierarchy is broken down to Level 2 which comprises the criteria and further down to Level 3 consisting of the sub-criteria while Level 4 will include the alternatives from where the most suitable choice will be made (Saaty, 1987).
In this study, Level 1 is the goal which implies "identification of suitable locations for bioenergy crop production" while Level 2 is the multi-criteria which consists of several criteria which may affect this, i.e. climate conditions, soil properties and topography. The third level consists of the six sub-criteria derived from the three main criteria, i.e.; temperature, rainfall, soil organic matter, soil pH, slope and elevation while level 4 are the key alternative choices (Gupta *et al.,* 2015) represented as "alternatives 1, 2, 3, 4, 5 and 6" to enable identification of the problem (Meng *et al.*, 2011). These are related to the six geo-political zones of Nigeria: the North Central, North East, North West, South East, South South and the South West (Figure 5.1.).

Several authors have used different hierarchical levels to make useful decision judgements. To this effect, Duc (2006) employed three hierarchal levels to achieve land suitability for coffee production in the Lam Dong Province of Vietnam. A study in Germany also used the same structure (three hierarchal levels) to identify suitable wind farm sites in the Aachen region (Höfer *et al.*, 2016). A further study in Malaysia, also employed three hierarchal levels to evaluate suitable locations for coastal management and planning (Bagheri *et al.*, 2012). According to a study in Northern China, a three hierarchal level structure comprising of the objective, factors and sub-criteria was used to assess land suitability for alfalfa production in the dry continental steppes (Deng *et al.*, 2014).

Synthesis of priorities: This is a case where priorities are being synthesized through level 2 downward and is achieved by multiplying local priorities by the overall goal and later summing up each of the elements based on their effects to their criteria (Hafeez *et al*., 2002; Saaty, 1987; Saaty, 1983).

Although AHP has been employed to solve several complex problems across the public and private sectors, it has been criticised particularly for its inability to provide sufficient guidance on how to structure the problem that is to be addressed. The model has no clue of how the hierarchal levels would be formed. This can be addressed by conducting the so-called "AHP Walk-throughs" (Alexander, 2012). This implies making appropriate consultations and work through examples to understand the concepts properly. However, despite these limitations the AHP method has been widely used, is easy to understand and has been applied as the leading approach for multi-criteria decision-making (Alexander 2012). Despite these limitations and based on its strengths as pointed out in the above studies, AHP was adopted for estimating land suitability in this research (Figure 5.1).

It is worth mentioning that there are several other approaches of MCDM like the weighted sum method (WSM) which is mostly used for single dimensional problems and the weighted product method (WPM) which is similar to the WSM but the difference is that the method uses multiplication rather than the product function. However, based on the difficulties experienced when applied to complex multiple dimensional decision making problems, these methods were not investigated further in this study.

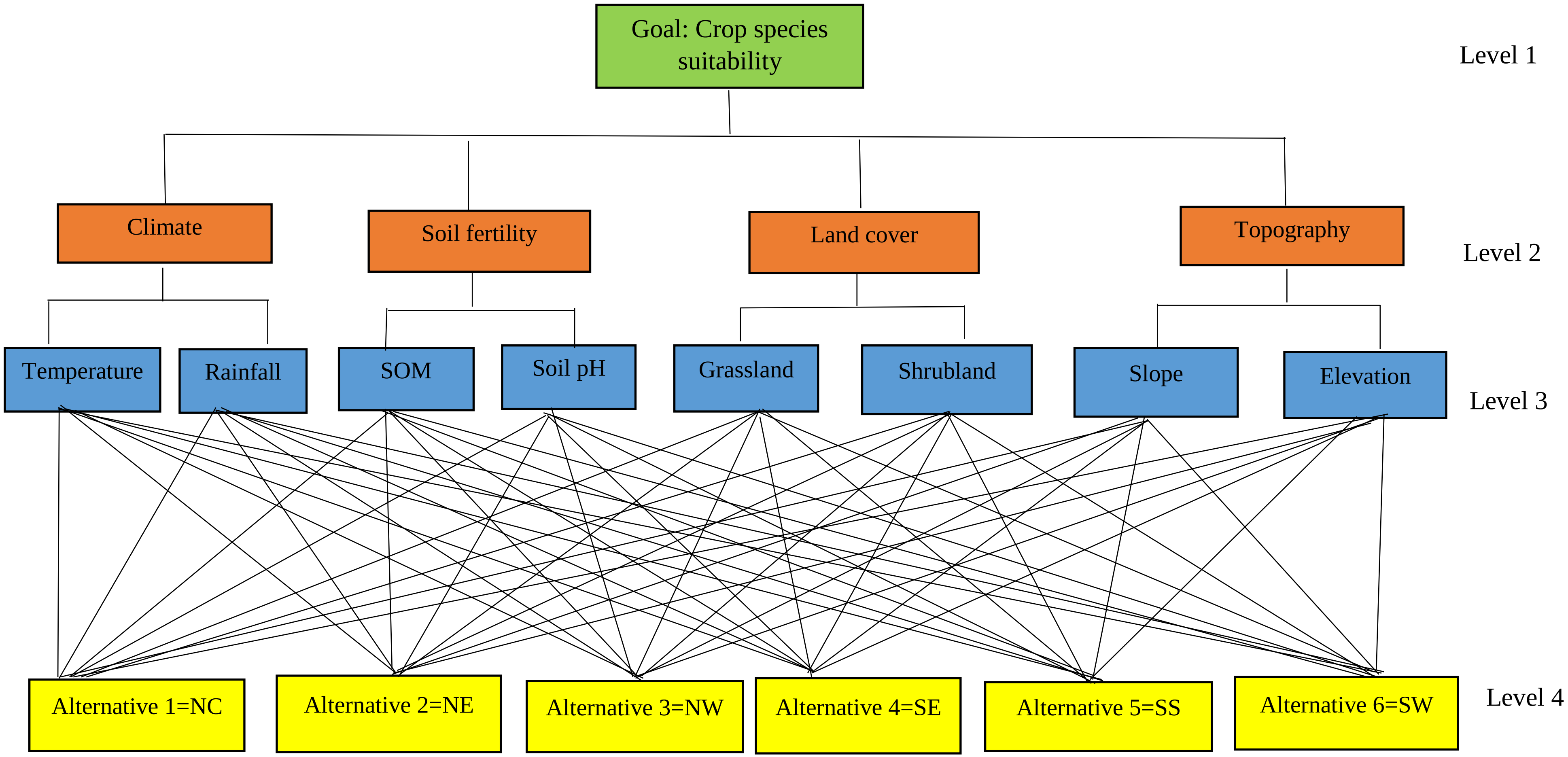

Figure 5.1: Hierarchical flow chart for choosing the best location for the selected bioenergy crop species

5.2.3 AHP-MCDM: Relative measurement of factors

In order to construct the pairwise comparison matrix (PWCM) for this study, a measurement scale with values ranging from 1 to 9 (Table 5.1) was used to score each criteria (Kumar *et al.,* 2013; Saaty 1987). As shown in Saaty, 1987, the even numbers, also known as the intermediates values were not included in the scale, since there was no compromise preference rating, rather only the absolute numbers which indicated equal importance (1), moderately important (3), strongly important (5), very strongly (7) and extremely important were used (Table 5.1).

Table 5.1: The fundamental scale of absolute numbers for PWCM (Saaty, 2008; 1987)

Intensity of importance	**Degree of preference and explanation**
1	Equal importance: This indicates two activities contributing equally to the objective/overall goal
3	Moderately important: this is applied when the judgment slightly favours one activity over another.
5	Strongly important: this is applied when experience and judgment strongly favour one activity over another.
7	Very strongly important: this is where it is very strongly demonstrated that an activity is favoured over another activity.
9	Extremely important: this implies that the evidence favouring one activity over another is of the highest possible order of affirmation.

As previously mentioned AHP relies on expert opinion. However, the scale for this research was constructed based on evidence comprised within the existing literature. The essence of employing literature-based information is that the experts' opinion is subjective. This will be particularly the case in Nigeria, where familiarity with herbaceous energy crops/grass production is limited. The values in Table 5.2 were also generated from similar studies that have successfully applied the fundamental scale of Saaty (1987) to compare and make useful decision judgements (Deng *et al.*, 2014; Ayehu and Besufekad 2015; Khioro *et al.*, 2013; Linda *et al.,* 2015; Jafari and Zaredar, 2010; Feizizadeh and Blaschke 2012).

Although, these studies (Table 5.2) are not entirely exhaustive but were adopted since they were the most recent and relevant publications in this area (Linda *et al.*, 2015, Ayehu and Besufekad 2015; Khioro *et al.,* 2013) to have been carried out in tropical regions (Nigeria, Ethiopia and Kenya) while Jafari and Zaredar (2010) as well as Feizizadeh and Blaschke (2012) were obtained from sub-tropical countries (Iran and China). These regions were presumed to have similar climate to the study area (Nigeria).

The studies in the tropics were identified to possess average annual temperature of 27^{o}C, elevation of 1830m and similar rainfall distribution as identified across the entire zones of Nigeria.

Further reasons for adopting these studies were due to the application of information from the literature to allow relative scores and weighting of the suitability factors.

The essence of identifying the estimated weights was to derive some of the scores which were not identified in some studies (Deng *et al.*, 2014; Linda *et al.*, 2015). To this effect, individual weights of the adopted suitability factors (temperature, rainfall, slope, soil pH, and SOM) as employed in the study (GIS-based approach for investigating the potential of herbaceous bioenergy crops for cellulosic ethanol production in Nigeria) were estimated in Ayehu and Besufekad (2015) as; 0.4345, 0.243, 0.0999 and 0.0436 respectively. Ayehu and Besufekad (2015) rated temperature as the most important factor with the highest score (7) compared to other factors, the study ranked rainfall as the second most important factor while soil pH was the least important factor. The subsequent factor weights and scores obtained from Ayehu and Besufekad (2015) were used as a baseline to rank and score the weights derived from the other studies (Table 5.2). Meanwhile, according to the last column at the left side (Table 5.2) average scores from factor weights temperature and land cover were rated as the highest criteria with a score of 7 each, rainfall 6, slope and soil organic matter with 4 each while soil pH (SpH) and elevation 2 and 3 respectively. The estimated scale was later used to generate the comparative matrix.

Table 5.2: Scoring of factors based on estimated weights derived from reviewed related study.

Factors	Estimated Weights from related literature						Average scores derived from the weight
	Deng *et al.*, 2014	**Ayehu and Besufekad, 2015**	**Linda *et al.*, 2015**	**Khioro *et al.*, 2013**	**Jafari and Zaredar, 2010**	**Feizizadeh and Blaschke, 2012**	
Temperature		0.4315 (7)	0.3076 (6)	0.4153 (7)	0.403 (7)	0.1823 (5)	7
Rainfall	0.2280 (5)	0.2418 (5)	0.4789 (7)	-	0.597 (7)	0.031(1)	5
pH	0.1152 (3)	0.0436 (1)	0.0389 (1)	0.0497 (2)	-	0.0328 (1)	2
SOM	0.0309 (1)		0.1019 (3)	-	-	0.2538 (6)	4
Slope	0.1379 (3)	0.0999 (3)	0.1160 (3)	-	0.589 (7)	-	4
Elevation	0.0276 (1)	-	-	-	0.403 (7)	0.0342 (1)	3
Land cover	-	-	-	-	0.4032 (7)	-	7

5.2.4. Determination of the pairwise comparison matrix (PWCM)

The matrix used to generate the PWCM is defined as *A*, where n is the number of criteria (i = row and j = column)

$A = [a_{ij}]$, i, j = 1, 2, 3…n where

aji = 1/ aij

expresses the reciprocal of A with the elements aij.

In this study (Table 5.3), the entry elements in row 1 (temperature) for example were compared with column 1 (temperature) to arrive at unity which implied that both the two elements (temperature) were of equal importance to each other as would be expected. For example, the elements of row 1 (temperature) were further compared with rainfall (column 2), soil pH (column 3), SOM (column 4), slope (column 5) and elevation (column 6). In this case, temperature was 2 times more important than rainfall, 5 times more important than both soil pH and SOM, 3 times more important than slope, and 7 times more important than elevation and 5 times more important than land cover (column 7). The second criterion was rainfall (row 2) which when compared with temperature (column 1) obtained a reciprocal value of 0.5 which indicated that rainfall is less important than temperature. When rainfall (row 2) was compared with rainfall (column 2) the result showed unity which indicated that the two elements were of equal importance to each other as expected. Rainfall was further compared to soil pH (column 3) and SOM (column 4) which showed that rainfall was 3 times i.e. moderately more important than soil pH and 5 times more important than SOM. The entire 6x6 matrix was completed for the rest of the elements before the output of the matrix score were subsequently summed for each column to obtain the sum total of the columns (Table 5.3).

Table 5.3: Pairwise Comparison matrix (PWCM) for the criteria

Factor	Temperature	Rainfall	Soil pH	SOM	Slope	Elevation	Land cover
Temperature	1.000	2.000	5.000	5.000	3.000	7.000	5.000
Rainfall	0.500	1.000	3.000	5.000	3.000	7.000	5.000
Soil pH	0.200	0.333	1.000	2.000	4.000	3.000	5.000
SOM	0.200	0.200	0.500	1.000	2.000	4.000	2.000
Slope	0.333	0.333	0.250	0.500	1.000	2.000	2.000
Elevation	0.200	0.200	0.200	0.500	0.500	1.000	2.000
Land cover	0.200	0.200	0.200	0.500	0.500	0.500	1.000
Sum	**2.63**	**4.27**	**10.15**	**14.5**	**14.0**	**24.5**	**22.0**

5.2.4.1 Normalizing the criteria

The comparative matrix *A*, was normalized using the expression:

$\sum_{i=1}^{n} w_i = 1$ where w = factor weight and n = number of criteria

Each entry unit of the decision matrix (Table 5.3) was divided by the column sum to determine the normalized values (A_{norm}). After the entire process, each column was equal to 1 indicating the proficiency of the estimation.

In order to estimate the factor weights, the sum total of each criteria i.e. temperature, rainfall, pH, SOM, slope, elevation and land cover was divided by the total number of criteria to obtain the average of each criteria (Table 5.4). The results showed that temperature has the highest weight which is the most important factor when assessing land suitability with about 0.345 (35%) followed by rainfall with 0.256 (26%), soil pH with 0.147 (15%) and soil organic matter with 0.091 (9.1%). Slope and elevation recorded about 0.073 (7.3%) and 0.049 (5%) respectively while land cover had the least priority weight of just 0.040 (4%).

Table 5.4: Weight criteria following normalisation of PWCW of criteria weight

Factor	**Temperature**	**Rainfall**	**Soil pH**	**SOM**	**Slope**	**Elevation**	**Land cover**	**Total**	**Weights**
Temperature	0.380	0.469	0.493	0.345	0.214	0.286	0.227	2.413	**0.345**
Rainfall	0.190	0.234	0.296	0.345	0.214	0.286	0.227	1.792	**0.256**
Soil pH	0.076	0.078	0.099	0.138	0.286	0.122	0.227	1.026	**0.147**
SOM	0.076	0.047	0.049	0.069	0.143	0.163	0.091	0.638	**0.091**
Slope	0.126	0.078	0.025	0.034	0.071	0.082	0.091	0.508	**0.073**
Elevation	0.076	0.047	0.020	0.034	0.036	0.041	0.091	0.344	**0.049**
Land cover	0.076	0.047	0.020	0.034	0.036	0.020	0.045	0.279	**0.040**
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000		

5.2.4.2 Estimation of consistency measures

In any analytical hierarchy process application it is always advisable to check that the criteria weights derived from PWCM are consistent. In this case, the consistency ratio (CR) is used to check the likelihood that the pairwise matrix was randomly generated (Ayehu and Besufekad, 2015).

To do this, there is the need to first determine the consistency index (CI) which was calculated as follows:

$$CI = \frac{(\lambda max - n)}{n - 1}$$

where maximum lambda (λ_{max}) is the principal eigenvalue of matrix A *and*

n = the number of comparisons made for the criteria or sub-criteria

The consistency ratio was obtained by dividing the estimated consistency index (CI) with the random index (RI). The random index is defined as the average of the resulting consistency index, based on Saaty's order of matrix.

$$CR = \frac{CI}{RI}$$

Table 5.5: Random Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty 1987)

From the results presented in Table 5.6: CI= 0.113; RI = 1.32 and CR = 0.086. The decision was accepted since $CR \leq 8.6\%$ is equivalent to the CR (0.092) indicated by Saaty, 1987.

The essence of this chapter was to estimate and identify the priority weights (w) of the selected criteria in order of their importance. Results of the AHP were integrated into ArcGIS model builder to carry out the suitability analysis using weighted overlay model.

Chapter 6: Evaluating the Suitability of Nigeria for Bioenergy crop Production

6.1 Evaluating the land suitability of the selected crop species

To enable suitability analysis for the C3 (alfalfa) and different C4 (elephant grass, *Miscanthus x giganteus* and switchgrass) species, known as warm-season, tropical plants, the ranges of the 7 selected factors were classified based on their suitability classes to support each crop (Table 6.1). The essence of these ranges were to classify the suitability classes of the processed GIS input layer datasets.

It was observed that the optimal maximum temperature required to support the suitability of the species is between 15 to 35^{o}C while temperatures < 10 ^{o}C are categorized not suitable for switchgrass, miscanthus and elephant grass. The rainfall requirement is between 400 - 1,600mm. The slope level required to enable identification of a suitable location for the species is between 1 to 8% while levels > 12% are not suitable (Table 6.1).

Further information on soil pH indicated that any level >8.3 is not suitable while optimum growth is achieved at 5.0 - 8.3. High altitudes i.e. >1,500m would not support successful production of the herbaceous species in Nigeria. Further classification processes for each species were carried out (Table 6.1) to identify all suitable classes that can support successful execution of the suitability analysis.

Finally, the weights of each factor i.e. temperature, rainfall, soil pH, SOM, slope, elevation and land cover datasets were multiplied with the input layer files to identify the most suitable Geopolitical zone for each of the selected bioenergy crops in Nigeria. Table 6.1 provides the suitability ranges for C3 and C4 species based on the existing literature.

6.2 GIS based Land suitability evaluation for selected bioenergy crops in Nigeria

In order to carry out land suitability analysis for each of the C3 and C4 species, the layer files were overlaid with the criteria. The suitability value was created using the weighted linear combination equation (Eastman, 1999);

$$S = \sum w_i X_i * \prod C_j \quad (4)$$

Where S = Suitability index

w_i = weight assigned to factor $_i$, with

$w_1 + w_2 + \ldots + w_m = 1$

X_i = criterion score of factor i

C_j = constraints $_j$ (Boolean value of limited criterion based on Duc, 2006)

The weighted linear combination has been applied by Duc (2006) to effectively combine AHP and GIS tools to carry out land suitability analysis in Vietnam.

In this study, ArcGIS 10.2 model builder was used to develop individual models for each selected bioenergy species in Nigeria (Fig 6.1a).

The weighted overlay tool is a technique which applies a common scale of values to dissimilar input datasets and generates suitability raster using criteria weights (Riad *et al.*, 2011) . This technique has gained global interest due to its capability to effectively resolve complex spatial problems associated with land suitability analysis and site selections.

To evaluate suitability scores, the weighted overlay tool was used to add all factor weights derived by employing AHP before the processed spatial layers were overlaid. Each criterion weight was checked to balance the percentage input rasters equally and sum the influence to

100. Also, an evaluation scale of 1 to 5 was selected from the ArcGIS weighted overlay and the input raster criterion entered to the appropriate field (Fig 6.1b). The resticted field option was employed in order to indicate areas that are excluded from the research such as bare land, built-up areas, crop land and water bodies. The exclusions were basically due to their various alternative land uses. The final suitability map was based on the best output data in association to the best area for cultivating each selected bioenergy species. The suitability map was classified into four land classes based on the FAO classification; i.e. Highly suitable, Moderately suitable, Marginally suitable and areas Not suitable for each species.

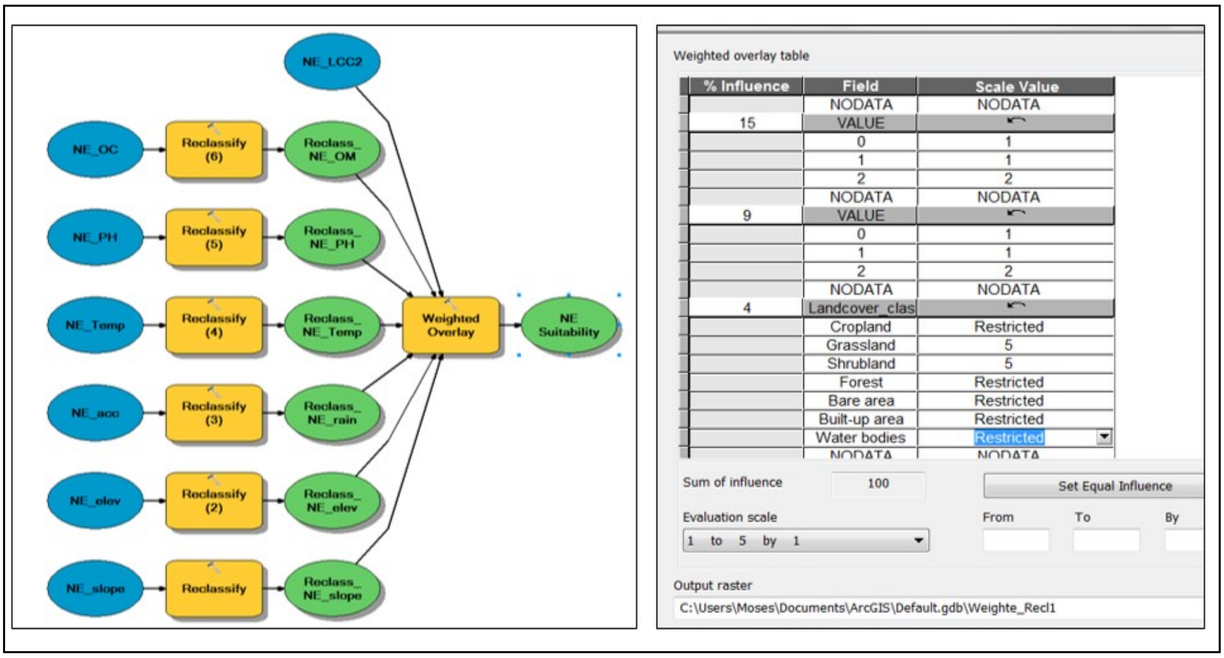

Figure 6.1: A land suitability model using weighted overlay to determine best areas for growing various bioenergy crop; Alfalfa, Elephant grass, *Miscanthus x giganteus* and Switchgrass in the 6 Geopolitical zones

6.3 Land suitability for alfalfa production

According to the results of the suitability analysis, three zones were identified as suitable for alfalfa production. Amongst these, the NE seems to be the most suitable in terms of land mass

(Fig 6.2). The zone has a total area of 27,424,584 ha of which 11,483,514 ha is suitable which was found particulary around the North-North-east (NNE) (Table 6.2). About 36% of the area found around the South-North-East (SNE) is also highly suitable, 5.8% moderately suitable while 58% is not suitable for alfalfa production (Appendix 23). The NC was identified as the second most suitable zone with 10,680,921 ha (Fig 6.2). Approximately 47% of the area is highly suitable for growing alfalfa, 0.4% only is moderately suitable while 52.9% is not suitable for alfalfa production (Appendix 23). The NW zone is the third most suitable location based on the total area i.e. 89,566,200 ha. The zone had a total suitable area of 8,008,434 ha (Fig 6.2; Appendix 23). According to the estimation, 36% of the area, particularly in the North-North-west (NNW) is classified as a highly suitable location, 1.8% in the South-North-west (SNW) of the zone is moderately suitable whereas a large part of the NW zone comprising of over 62% was predicted not suitable for alfalfa production (Fig 6.3a; Appendix 23). Further evaluation of the land suitability analysis indicated that the SW zone is the most suitable location in Southern Nigeria for growing alfalfa (Fig 6.3d). The zone recorded about 5,513,625 ha (Fig 6.2; Table 6.2) where almost the entire East-South-west (ESW) part comprising of about 70% was identified to be highly suitable, about 1.9% which was located around the North-South-west (NSW) was estimated to be moderately suitable, while 26% of the area which was mainly located around the West-South-west is deemed unsuitable for the crop (Fig 6.3d, Appendix 23).

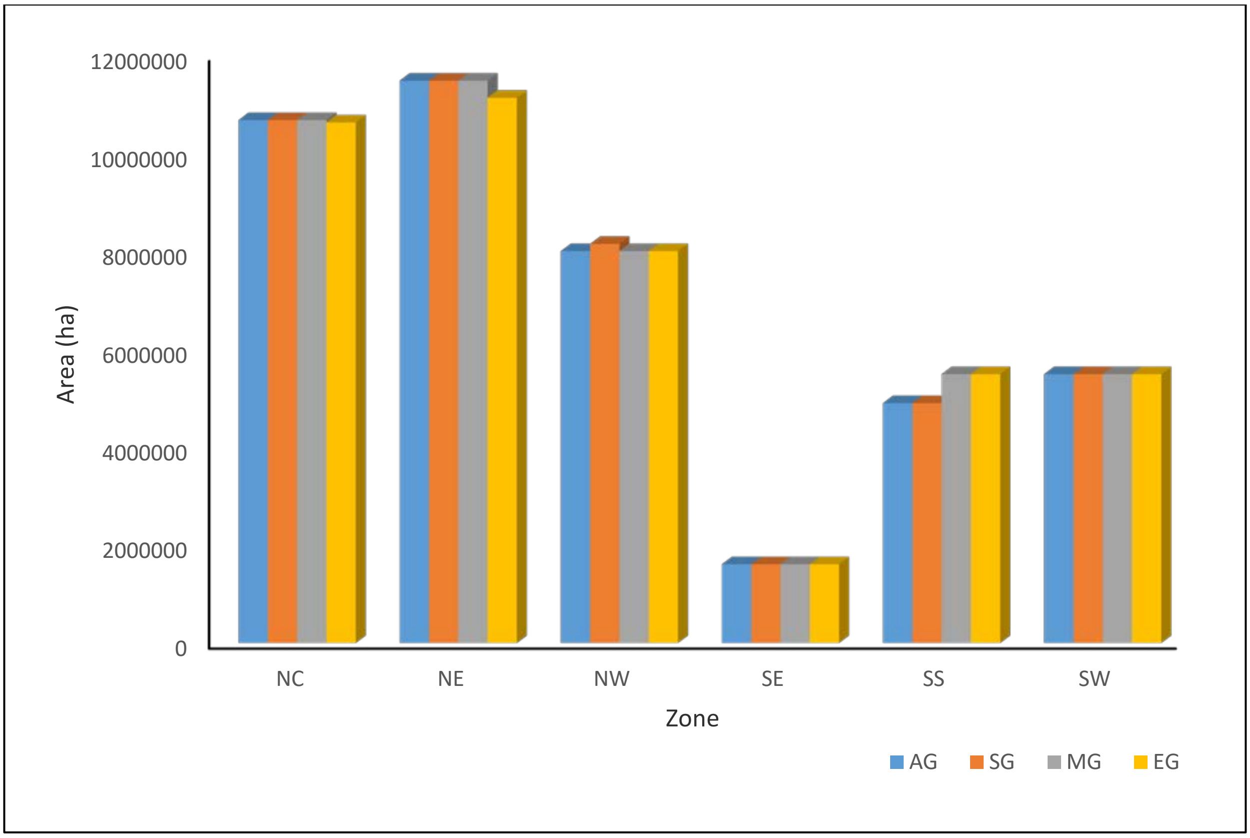

Figure 6.2: Evaluating the most suitable zone for the selected species (AG; Alfalfa, SG; Switchgrass, MG; *Miscanthus x giganteus* and EG; Elephant grass).

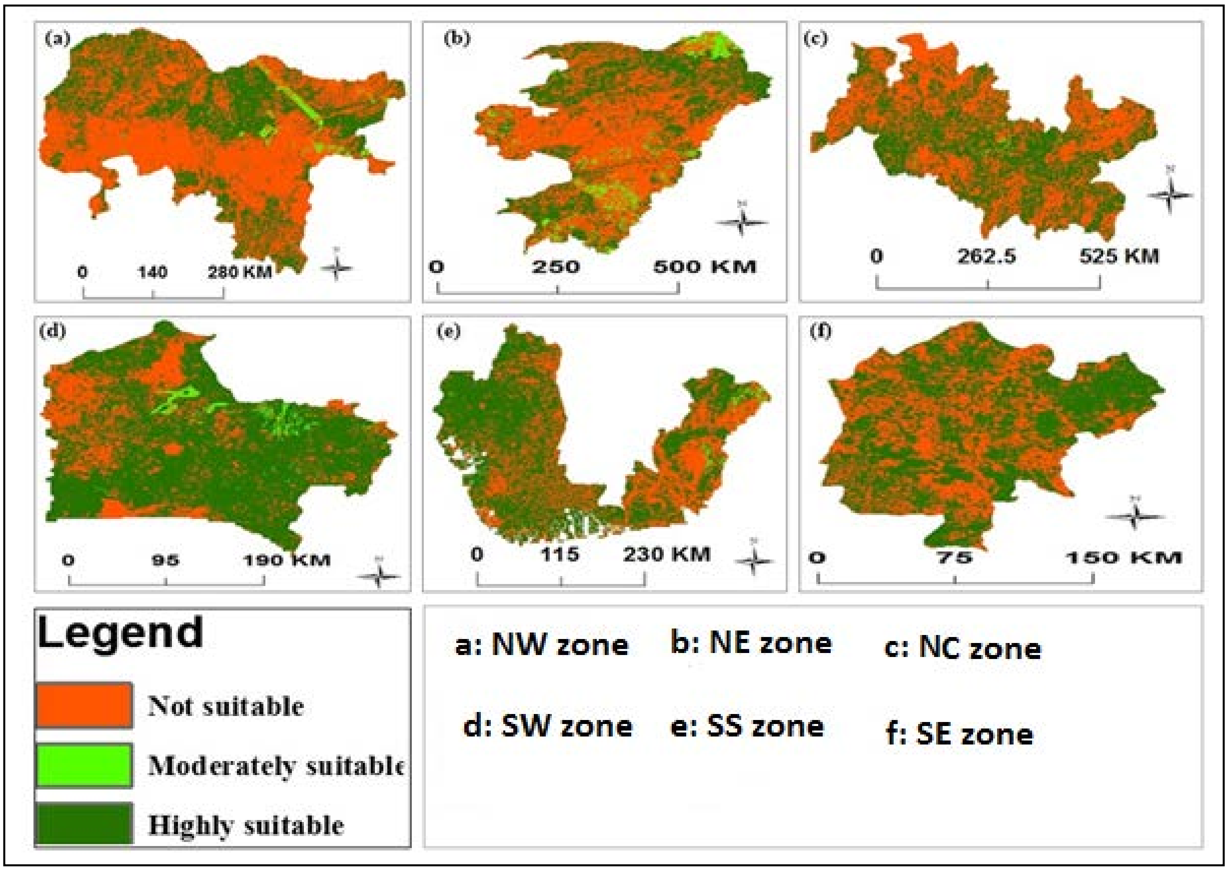

Figure 6.3: Suitability of Alfalfa (AG) in the six Geopolitical zones of Nigeria

The SE zone was identified as the least suitable location for growing alfalfa, in terms of total area (Fig 6.2) although 58% of the area is highly suitable, while 43% is not suitable for growing the species (Appendix 23). The SS zone is the second most suitable in the South of Nigeria (Fig 6.2). Here, over 61% of the area predominantly around the West-South-south (WSS) location is highly suitable, only ~ 1% is moderately suitable, whereas about 38% is located across the East-South-south is not suitable for growing alfalfa (Appendix 23; Fig 6.3e).

6.4 Land suitability for elephant grass production

Suitability analysis for elephant grass showed that the NE also possessed the highest suitable area in Nigeria with a total area of 11,133,846 ha (Fig 6.4b; Fig 6.2. Table 6.2). The NE zone was identified to possess about 5.8% of highly suitable locations. This highly suitable area was located particularly around the NNE location (Fig 6.4b). Also, ~36% of the area around the NNE was moderately suitable while over 58% of the area was not suitable for elephant grass production (Appendix 22). The NC zone recorded the second most suitable area for elephant grass production, in terms of land mass, the zone had about 10,631,400 ha (Fig 6.2). Approximately 41% is highly suitable for growing the energy crop, 6.4% is moderately suitable area while ~53%, which was located mainly around the North-North-central (NNC) area is not suitable for elephant grass production (Appendix 24; Fig 6.4c). Although, the NW zone had a total suitable area of 8,009,550 ha (Fig 6.2; Table 6.2), the zone is not recommended for growing elephant grass since over 50% (62%) is not suitable whereas only 8% is highly suitable and about 30% moderately suitable for the crop (Fig 6.4a; Appendix 22).

In terms of the evaluation for most suitable location in Southern Nigeria, the SW geopolitical zone had the highest suitable area i.e. 5,513,625 ha (Fig 6.2; Table 6.2). In the SW zone, about 74% is highly suitable while 26% predominantly found in the WSW location is unsuitable for elephant grass production (Fig 6.4d; Fig 6.2). The SS zone has a total suitable area of 4,887,279 ha (Appendix 22), of which ~27% located in the west is highly suitable, 35% located around the South-South-south is moderately suitable while 38% found in East-South-south is unsuitable for growing the bioenergy species (Fig 6.4e; Appendix 22). The total suitable area for elephant grass production in the SE zone is only 1,636,353 ha (Fig 6.2; Table 6.2). Results (Appendix 22) showed that a large portion of the area (~50%) found evenly spread over the entire zone is said to be moderately suitable, 8% is highly suitable, while 43% is not suitable for the species (Appendix 22).

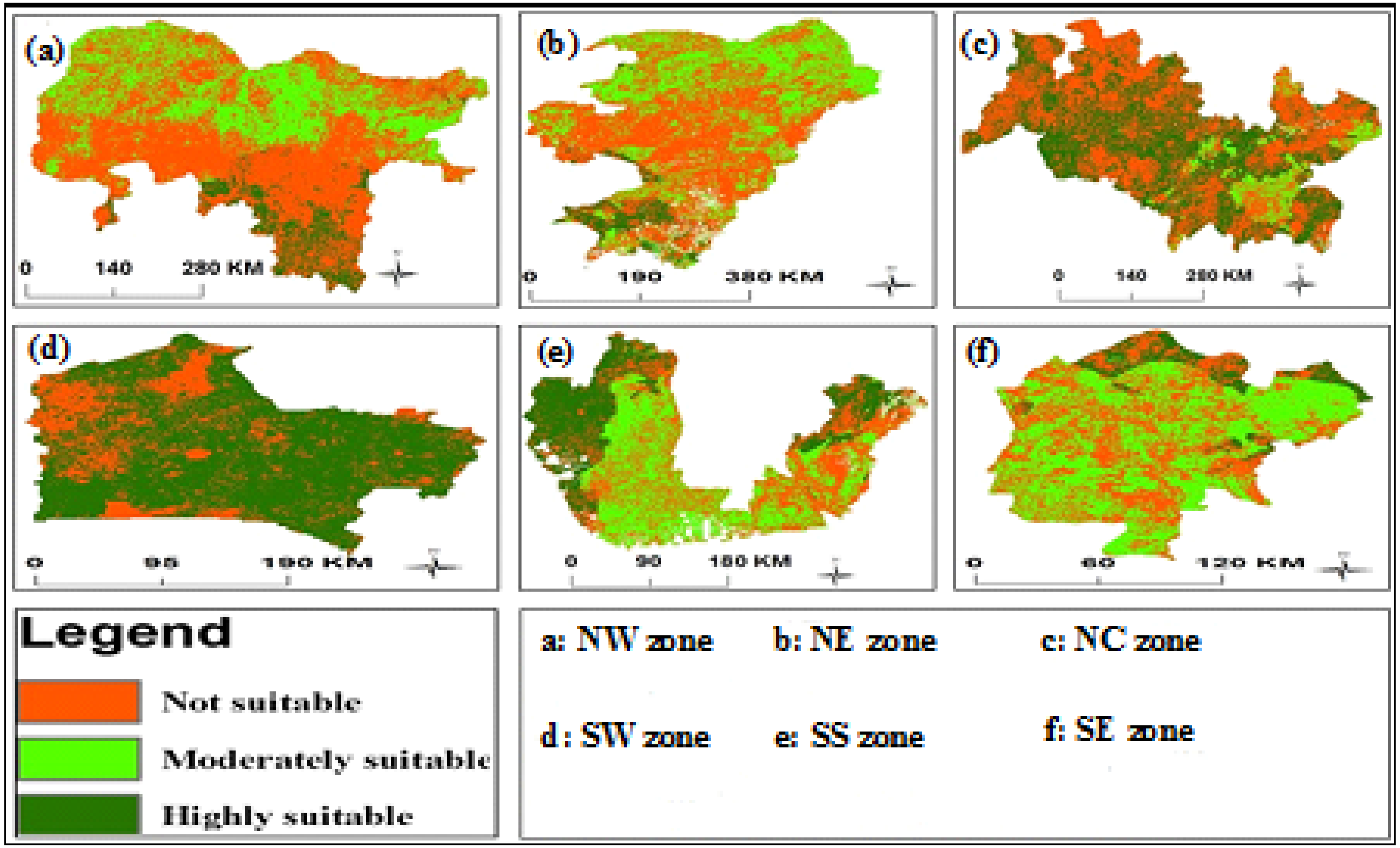

Figure 6.4: Suitability of the six Geopolitical zones of Nigeria for Elephant grass (EG) production.

6.5 Land suitability for *Miscanthus x giganteus* production

In terms of evaluating the suitability for *Miscanthus x giganteus* production, the NE zone is identified as the most suitable zone with about 11,483,500 ha (Table 6.2). The NNE of the zone is identified to record about 42% of the total areas classified to be highly suitable for the species. Over 50% of the zone is deemed unsuitable for growing the species (Fig 6.5b; Appendix 21).

The NC zone recorded a total of 10,680,900 ha (Fig 6.2). About 29% of the total suitable land found around the West-North-central (WNC) is rated as highly suitable, 18% is moderately suitable and over 53% is not suitable for the species (Appendix 21; Fig 6.5c). The NW zone possessed a total suitable area of 8,009,600 ha (Fig 6.2; Table 6.2), of which 5.1% identified around the South-North-west (SNW) is highly suitable for the species. It was observed that mainly areas around the West-North-west (WNW) were identified as the best location for growing this crop. About 33% of this area is indicated as moderately suitable, but the major limitations for investing in this location is basically due to 62% of the land area being classified as unsuitable for *Miscanthus x giganteus* cultivation (Fig 6.5a; Appendix 21).

In a land mass context, the South of Nigeria has less suitable areas than the North (fig 6.2), with the SW geopolitical zone having the most potential area in the South of the country (Fig 6.5d). The SW zone recorded about 74% of suitable area compared to 26% identified as unsuitable for *Miscanthus x giganteus* (Appendix 21). The SS zone has a total suitable area of about 4,924,100 ha and the SE zone the least (1,636,400 ha) in terms of land mass (Fig 6.2; Table 6.2; Fig 6.5e & f). About 1.6% of the SS area is classified as highly suitable for *Miscanthus x giganteus*, 56% moderately suitable and ~ 10% is identified to be marginally suitable while only 4% of the total area is not suitable for *Miscanthus x giganteus* production (Appendix 21; Fig 5.4e). Also, about

48% of the area is moderately suitable in the SE zone, while 43% is identified as unsuitable (Appendix 21).

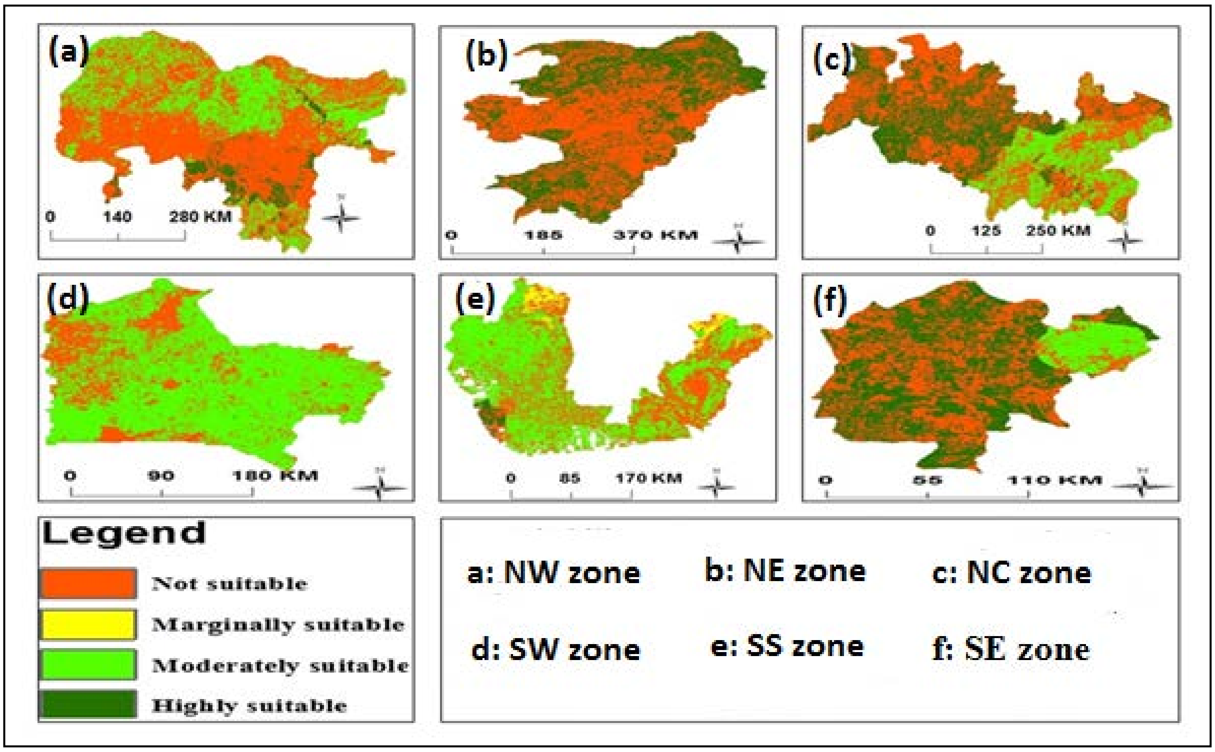

Figure 6.5: Suitability of the six Geopolitical zones of Nigeria for *Miscanthus x giganteus* production.

6.6 Land suitability for Switchgrass in the six geopolitical zones of Nigeria

According to results of the suitability analysis for switchgrass production, the NE recorded about 11,483,500 ha of total suitable land (Fig 6.2, Table 6.2), 2% of the area is classified as highly suitable, 39% moderately suitable and 2% found in the SNE Nigeria was rated as marginally suitable (Fig 6.6b; Appendix 20). According to the evaluation, the central location consisting of 58% was considered unsuitable for growing switchgrass (SG) in the NC zone. The NC zone had over 10,680,930 ha of total suitable area (Fig 6.2; Table 6.2), 7% is rated highly suitable and

35% as moderately suitable (Fig 6.6c; Appendix 20). About 5% of the South-North-central (SNC) is classified as marginally suitable to grow the feedstock (Fig 6.6c), while 53% is not suitable for switchgrass production (Appendix 20). The NW zone has a total suitable area of 8,155,404 ha, of which 33% is highly suitable, 6% moderately suitable while 62% is not suitable for cultivating switchgrass (Fig 6.6a). The SW is the main hotspot zone in terms of the required suitability conditions (Fig 6.6d). Although the zone recorded only about 5,513,643 ha as suitable, however 74% of this area is highly suitable (Fig 6.2; Table 6.2; Appendix 20). There is no doubt the high productivity of this zone and is therefore greatly recommended for the policy makers for the biofuel feedstock production since only 26% was identified as unsuitable for switchgrass (SG) production (Fig 6.6d; Appendix 20). The SS zone had total suitable area of 4,924,080 ha (Fig 6.2), of which only 6% is highly suitable, with over 50% of the area moderately suitable while 38% is not suitable for SG production. The SE Geopolitical zone had the least suitable area (1,636,443 ha) for producing switchgrass (Fig 6.6e; Appendix 20). It was indicated that the zone recorded over 50% of highly suitable area but 42% of unsuitable locations (Appendix 20). Although the SE zone has no specific concentrated location for the SG species but the East-Southeast location of this zone has clear potential for cultivation (Fig 6.6f).

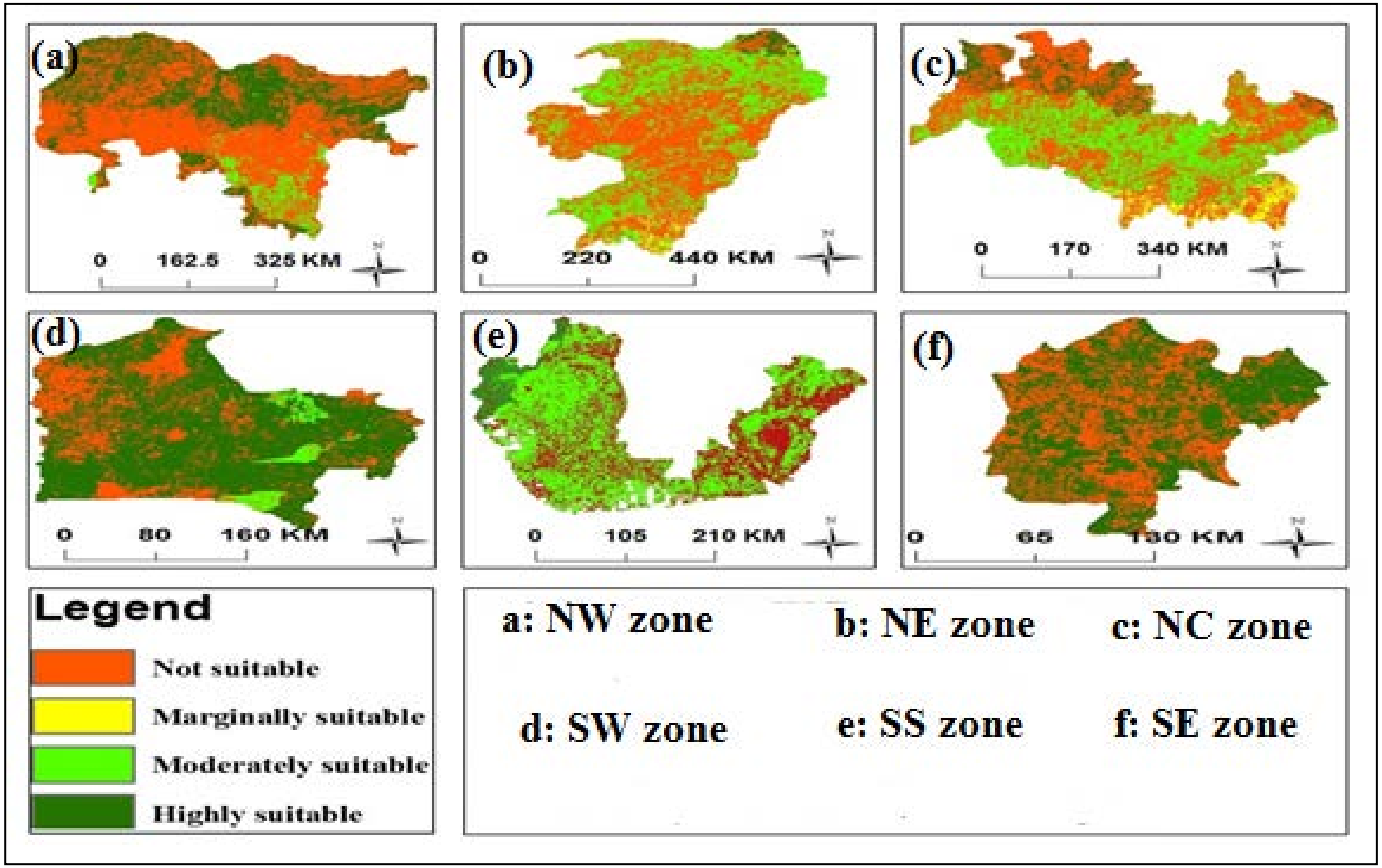

Figure 6.6: Suitability of switchgrass (SG) in the six Geopolitical Zones of Nigeria

Table 6.2: Summary of suitability of the 6 Geopolitical zones for the different bioenergy crop species.

Alfalfa	Zone	Highly suitable (ha)	Moderately suitable (ha)	Marginally suitable (ha)	Not suitable (ha)	Suitable (ha)
	NC	10585728	95193	-	11995137	10,680,921
	NE	9888759	1594755	-	15941070	11,483,514
	NW	7620318	388116	-	13188042	8,008,434
	SE	1636434	-	-	1208466	1,636,434
	SS	4856103	67977	-	3009564	4,924,080
	SW	5371668	141957	-	1976913	5,513,625
	Total	39,959,010	209934	-	47,319,192	**40,168,9440**
Elephant grass	NC	9190971	1440513	-	11947608	10,631,484
	NE	1544355	9589491	-	15581979	11,133,846
	NW	1632303	6377247	-	13188519	8,009,550
	SE	226449	1409904	-	1208367	1,636,353
	SS	2106648	2780631	-	2969694	4,887,279
	SW	5512851	774	-	1976913	5,513,625
	Total	20,213,577	21,598,560	-	46,873,080	**41,812,137**
Miscanthus x giganteus	NC	6551928	4128993	-	11995137	10,680,921
	NE	11480814	2700	-	15941070	11,483,514
	NW	1079343	6930207	-	13188519	8,009,550
	SE	-	1366461	269973	1208466	1,636,434
	SS	128538	4451220	344322	3009564	4,924,080
	SW	4851	5508774	-	1976913	5,513,625
	Total	19,245,474	22,388,355	344,322	47,319,669	**41,633,829**
Switchgrass	NC	1660842	7882695	1137393	11995137	10,680,930
	NE	451710	10567692	464112	15941079	11,483,514
	NW	6961059	1194345	-	13042710	8,155,404
	SE	1636400	100	-	1208500	1,636,500
	SS	483993	4440087	-	3009564	4,924,080
	SW	5214141	299502	-	1976913	5,513,643
	Total	16,408,145	24,384,421	1,601,505	47,173,903	**42,394,071**

Although the climatic conditions of Nigeria seem favorable for cultivating the species by producing similar results especially for the C4 species, they are indicated as being slightly more favorable to the C3 species. To this effect, switchgrass recorded the highest potential suitable locations across the entire country with 42,394,071ha, elephant grass and *Miscanthus x giganteus* with 41,812,137 and 41,978,151 ha respectively while alfalfa recorded 40,168,944 ha (Table 6.2).

6.7 Evaluation of the most suitable states in the Northern region for bioenergy crop production.

According to the suitability evaluation, Borno state in the NE zone was identified as the most suitable state in Northern Nigeria based on total land area of about 3,336,084 ha. Results indicated that Borno state possessed about 50% suitable areas. The North coast of the state recorded 46% of highly suitable land for alfalfa production, while the South had 48% of the area not suitable for growing alfalfa (Fig 6.7a; Fig 6.8).

Taraba state in the NE zone was considered as the second most suitable state for alfalfa production. The state recorded a total suitable area comprising of the highly and moderately suitable locations at about 2,720,300 ha for alfalfa production. 36% is highly suitable for the crop, ~10% moderately suitable and ~54% not suitable for production (Appendix 25; Fig 6.8). The state was found to record very similar suitable areas at 2,720,322 ha for the production of switchgrass (Appendix 26) and *Miscanthus x giganteus* relatively less suitable area for elephant grass production at 2,471,490 ha (Fig 6.8). Approximately 39% of which is highly suitable, only 7% is moderately suitable while ~54% is not suitable for the crop (Appendix 27). For elephant grass, 26% of the area was identified to be highly suitable, 20% moderately suitable and 54% classified as unsuitable area (Appendix 28). In terms of *Miscanthus x giganteus*, 50% of the area was estimated to be highly suitable and the remaining 50% not suitable for production (Appendix 27).

Gombe state which is also located in the NE zone of Nigeria was classified as the least suitable state in the North, the state was confirmed to record a very similar total suitable area at 291,150 ha for growing alfalfa, *Miscanthus x giganteus* while according to the estimation about 282,771 ha is suitable for elephant grass production (Appendix 28). The state was indicated to possess very high rate of unsuitable locations for the species. In terms of alfalfa cultivation, 13% of the area is highly suitable, 3% is moderately suitable while ~84% was rated unsuitable for crop production (Appendix 25). Results of *Miscanthus x giganteus* suitability evaluation, indicated that 16% of the area is moderately suitable while 84% was classified as unsuitable for growing the species (Appendix 27).

In terms of alfalfa suitability evaluation, Yobe and Bauchi states had total suitable areas of 2,133,432 ha and 1,702,827 ha respectively (Fig 6.8; Appendix 25). Of which 47% of the area in Yobe state is highly suitable for alfalfa production, while 52% is not suitable for the species. For Bauchi state, approximately 32% is highly suitable while 65% is not suitable for the species. For switchgrass production, Yobe recorded a total suitable area of 2,133,432 ha, where about 50% is suitable while 50% was indicated unsuitable for switchgrass production. For Yobe state, 34% of the area is suitable and 65% is not suitable for switchgrass production. For *Miscanthus x giganteus* production, Bauchi recorded a total suitable area of about 1,702,827 ha where 48% of the area is highly suitable while 52% is not suitable for growing the species (Appendix 27; Fig 6.8). The results for elephant grass production, indicated that Yobe had a total suitable area of 1,688,634 ha. Only 3% is highly suitable, ~32% moderately suitable but over 65% of the area is not suitable for growing elephant grass (Appendix 28).

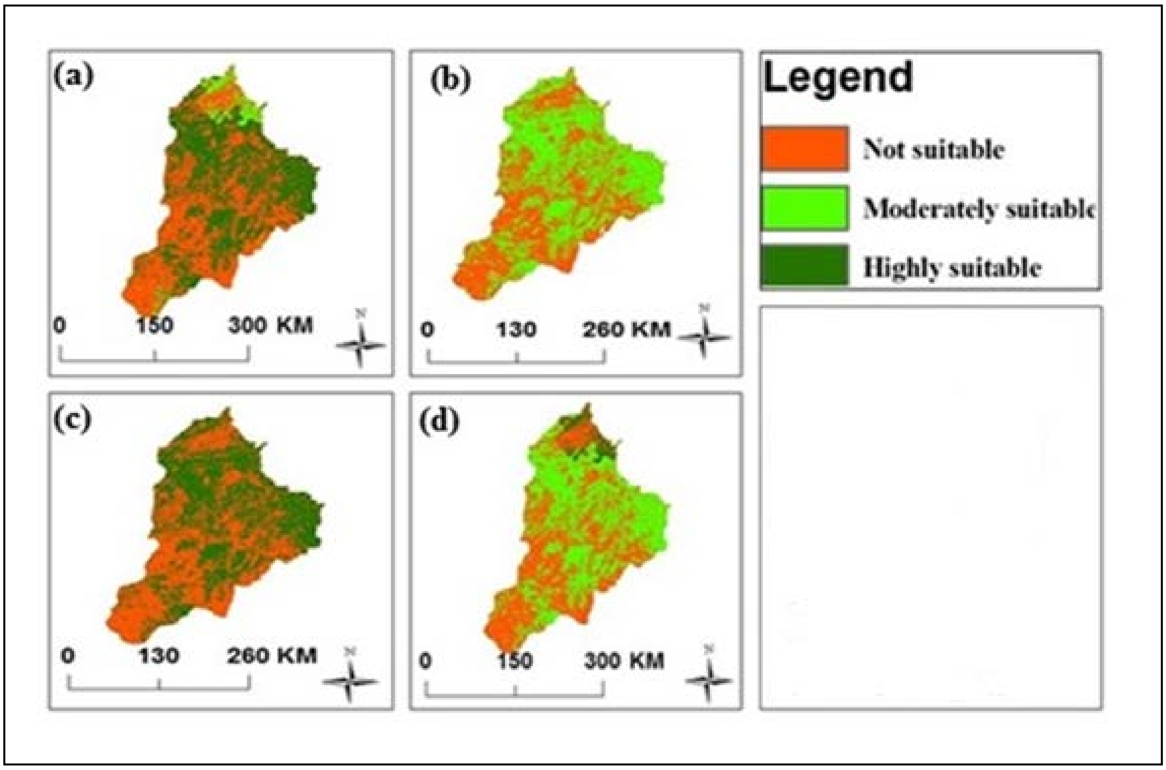

Fig. 6.7: Evaluating the potential of Borno state for a) Alfalfa (AG), b) Elephant grass (EG), c) Miscanthus x giganteus (MG) and d) Switchgrass (SG) production.

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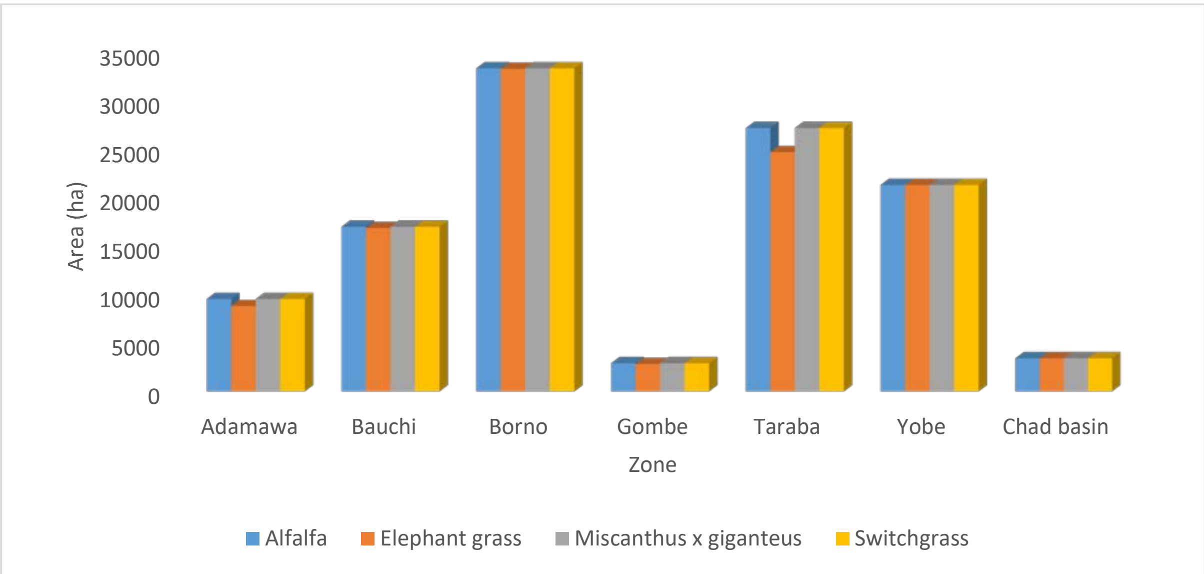

Figure 6.8: Evaluating the most suitable states for the selected species in North of Nigeria

6.8 Evaluation of the most suitable states in the South for bioenergy crop production

In terms of land mass, Oyo state recorded a total suitable area of 1,683,783 ha to be rated as the most suitable state for alfalfa production in Southern Nigeria (Fig 6.9a & 6.10). The state recorded ~60% of highly suitable area, 2.3% as moderately suitable while over 38% was not suitable for growing alfalfa (Appendix 29). Ondo and Ogun states recorded total suitable areas of 1,222,722 and 1,238,445 ha for alfalfa production respectively (Fig 6.10; Appendix 29). Ondo state possess over 85% of highly suitable land, while about 14% is not suitable for growing the species. Ogun state recorded ~77% of highly suitable area, while about 21% is not suitable for growing alfalfa. Lagos state had the least suitable location with about 157,815 ha, although of this, ~48% was of highly suitable area, while 52% was unsuitable for cultivating alfalfa. Although, Osun recorded a total suitable area of only 771,687 ha (Fig 5.9, Appendix 8), it was identified as an exceptional state in terms of high suitability conditions such as climate, topography and soil fertility to enable extremely high productivity. To this respect, Osun recorded about 80% of highly suitable area, with only 16% not suitable for growing alfalfa. Ekiti state had a total suitable area of 439,002 ha, where 78% is highly suitable for the species, while about 16% is not suitable for alfalfa production (Appendix 29). As indicated from the suitability analysis based on land area, Ogun and Ondo states recorded 1,238,445 ha and 122,274 ha for alfalfa production respectively (Fig. 5.9). Ogun had about ~80% of suitable areas compared to about 21% of the areas that was classified unsuitable for alfalfa. Also, Ondo state had over 85% of suitable areas while only 14% of the total area of was not suitable for alfalfa (Fig 6.10; Appendix 29).

In respect to land suitability analysis for switchgrass production based on total land areas, Oyo recorded the most suitable area with a total of 1,683,783 ha (Fig 6.9d & 6.10). The state had about 62% of suitable areas and 38% of area deemed unsuitable for switchgrass. (Appendix 30). Ondo and Ogun states recorded about 1,222,740 ha and 1,238,445 ha respectively, 75% is highly suitable, about 11% is moderately suitable while over 14% not suitable for switchgrass production (Fig 6.10, Appendix 30). Lagos state possessed a total suitable area of about 157,815 ha, of which about 50% is suitable, while 50% is not suitable for switchgrass production. Ekiti state had a total of 439,002 ha, 72% is highly suitable, and ~12% is moderately suitable while 13% was identified not suitable for growing switchgrass (Fig 6.9d & 6.10; Appendix 30).

Oyo state was also indicated to possess most suitable locations for *Miscanthus x giganteus* in Southern Nigeria. The state recorded about 62% of suitable area and about 38% not suitable for the crop (Appendix 31). Ogun and Ondo state had the second largest suitable areas in the South. The states recorded about 1,238,508 ha and 1,222,686 ha respectively (Fig 6.9c & 6.10). Over 78% is suitable and 21% not suitable in Ogun state while Ondo state recorded over 85% of suitable area 14% of the areas identified not suitable for the species. Osun state had a total suitable area of 771,615 ha, of which 84% are suitable while ~16% were classified not suitable for *Miscanthus x giganteus* (Fig 5.9; Appendix 33). Ekiti state recorded a total suitable area of 438,975 ha, where 84% was estimated to be suitable and 13% not suitable for the crop. Again, Lagos state was further classified as the least suitable location for *Miscanthus x giganteus*. The state recorded a total suitable area of 157,680 ha, where about 50% is suitable and the remaining 50% classified as unsuitable area for crop production (Fig 6.10; Appendix 31).

The suitability evaluation of Southern Nigeria for elephant grass production indicated that Oyo state again has the highest suitable land for growing the crop based on the total land suitability area (Fig 6.9c). The state recorded about 62% of suitable land and 38% of unsuitable areas for *Miscanthus x giganteus* cultivation. Ondo had 86% of 1,222,686 ha as moderately suitable for the crop and 14% as unsuitable land for growing the crop. Ogun state accounted for 1,238,508 ha of suitable areas, of which is 78% highly suitable while 21% is not suitable for the crop (Appendix 31; Fig 6.10).

Based on evaluation of the suitable locations for elephant grass production in Nigeria, Lagos state recorded a total of 157,680 ha, about 50% is again identified as suitable areas for growing the crop while 50% is not suitable (Fig 6.10; Appendix 31). Ekiti state with a total of 438,975 ha, accounted for 84% of suitable areas and 16% of areas not suitable for the species (Fig 6.10; Appendix 31). Osun state also recorded about 771,687 ha of which over 84% is suitable, while 16% is not suitable for elephant grass production in the state (Fig 6.10; Appendix 31).

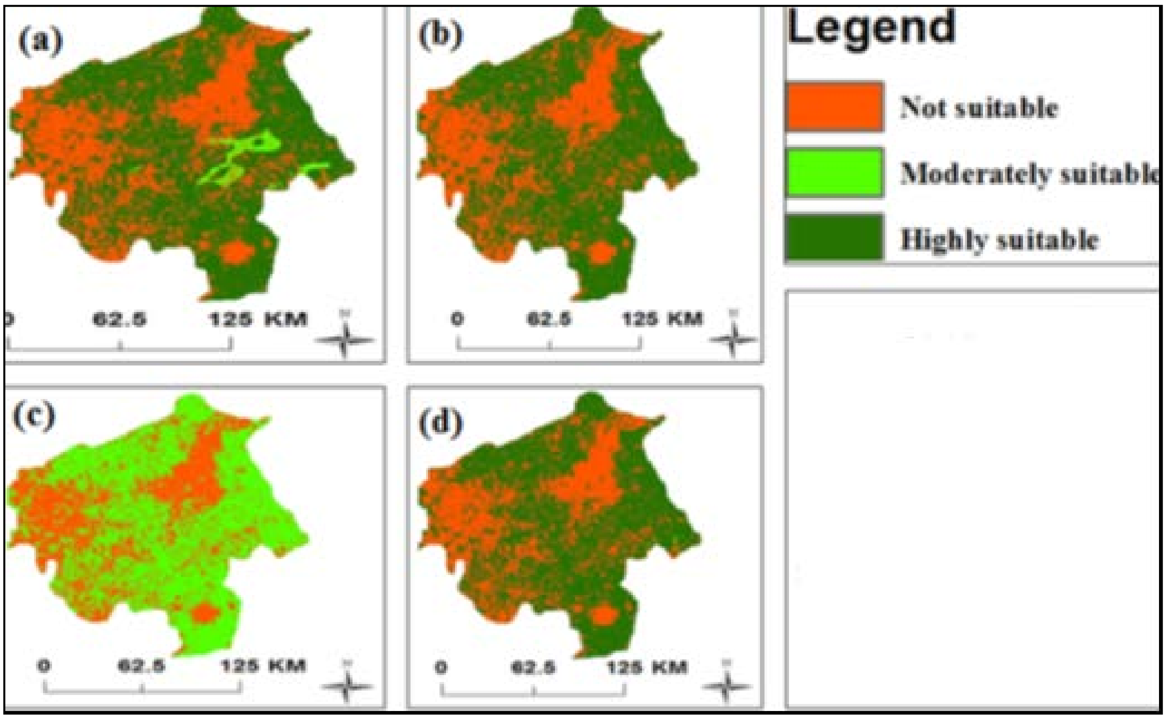

Figure 6.9: Evaluating suitability of Oyo state in Southern Nigeria for a) Alfalfa (AG), b) Elephant grass (EG), c) *Miscanthus x giganteus* and d) SG Switchgrass production.

The identified suitable areas will be used to estimate the productivity of the crops and also identify the most productive states and zones based on their suitability conditions.

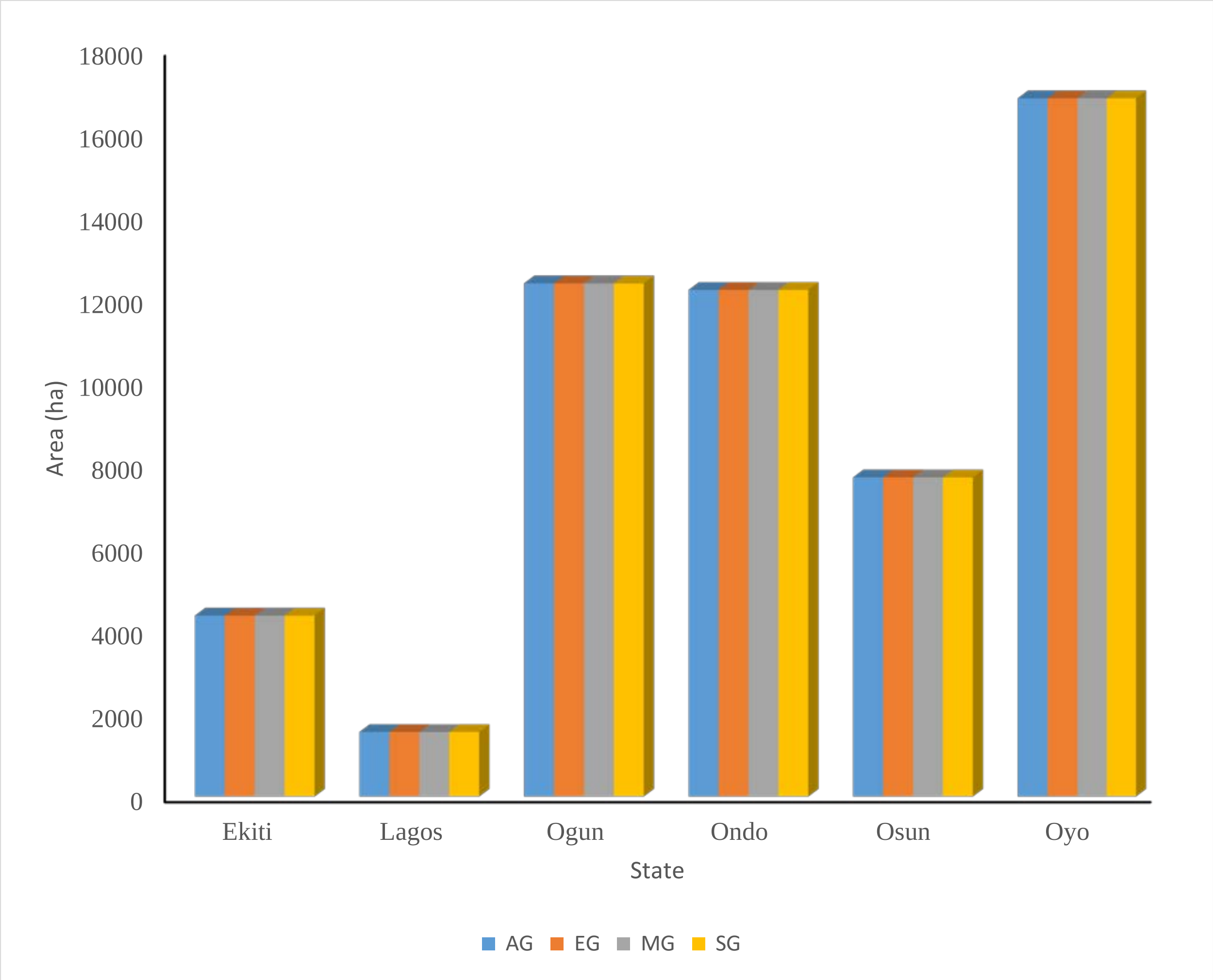

Fig 6.10: Evaluating the most suitable states in the Southern Nigeria for the selected species.

Chapter 7: Estimating land productivity of herbaceous bioenergy crops in Nigeria.

The productivity of the selected bioenergy crops was determined using the output data derived from the suitability maps. The suitability output datasets were integrated into developed python script with information extracted from previous related studies in the literature on the yield performance of the various crop species (Table 7.1).

7.1 Justifications for adopting information from the Southern United States

This information was used based on the similar temperature and rainfall ranges between the Southern parts of the Sub-tropical region of the United States and the study areas. The temperature ranges of this region particularly the South Central and South-western United States such as Texas and Oklahoma is between 30^{o}C to 36^{o}C (Henderson and Muller, 1997) which is as high as the temperature ranges experienced in Nigeria. This information was supported by Ingram *et al.* (2013) who indicated that Southern Florida normally has an average daily minimum temperature of 15^{o}C during the winter periods and 35^{o}C across Mississippi River valley and Southern Georgia during summer. The study further stated that these locations including the Gulf Coast of Louisiana as well as Alabama receive over 60 inches of rain (1524 mm) while South-western North Carolina receives as high as 100 inches (2,540 mm) average annual precipitation. In terms of elevation, the Alabama area has elevations up to 1500 to 300 feet (451 to 914 meters) whereas as high as 200 to 6600 feet (600 to 2012 meters) were found in Appalachians, Alabama, Georgia as well as Kentucky (Ingram *et al.*, 2013). The aim was to estimate the productivity of the selected bioenergy crops in the six Geopolitical zones as well as enable identification of the most productive states in Nigeria. The results of these studies (Table 7.1) were used due to locations of the studies in sub-tropical regions with a similar climate. The climatic conditions and other required factors were similar to the field conditions of Nigeria. Also the information on alfalfa from a study in Saudi Arabia (Kayad *et al.,* 2016) was used since the crop was found to successfully grow at mean annual rainfall >150 mm (Almazroui *et al.,* 2012) where irrigation is highly recommended. The annual temperature of the Southern Peninsula region was indicated as between 24 to 27 °C. In Dhahran, the hot days normally have a maximum temperature (Tmax) and minimum temperature (Tmin) of ≥ 35 °C and >20 °C (nights) while during the cold days, a Tmax of ≤ 20 °C and Tmin ≤ 15 °C (nights). The monthly mean Tmax and Tmin temperatures around July are 35.63 and 15.28 ° respectively across Dhahran. The Tmax around November is 19.7 °C and a Tmin of 9.1 °C in August (Rehman, 2010).

7.2 Application of GIS and Python based method for productivity evaluation

In order to employ Python software, input and output files were created to enable the storage of the processed and unprocessed datasets. The workspace environment was set to overwrite. The temporal files and the local variable files for storing and manipulating all raster datasets was converted to ASII formats. In order to run the program, the input dataset was saved in an appropriate directory designed for the output datasets (Appendix 50).

Python software was used to develop the scripting code which was first used to re-classify the suitability classes by merging the Marginally suitable and Moderately suitable areas to form one suitability class (Moderately suitable). The essence of the re-classification process was due to the limited number of cells from the initial suitability analysis which were classified as Marginal suitable areas. To this effect, both the Marginal and Moderately suitable areas were dissolved to form 3 classes using python software. Marginal classes were identified in some zones due to their topographical nature, i.e. areas having between 7 to 10^{o} and 1000 to 2100m. These areas that are marginally suitable was very small and required to be added to the moderately suitable locations. The suitability maps were converted from raster to ASCII format before the productivity of each species was finally estimated.

These derivations (Appendix 50), were carried out using Arc toolbox to convert the suitability raster files (data) to ASCII format. During the conversion process, the ASCII file was stored in an output folder to enable Python access to the datasets during programming. The converted datasets were later integrated and run using Python software to produce the productivity maps for each crop. The productivity maps were later integrated into ArcGIS Field calculator to estimate the total productions and percentage of each crop by multiplying the suitable areas by the total yield. Several studies have applied Python software to assess agricultural land suitability for the production of different crops in the tropical and sub-tropical regions based on their geo-environmental factors. Also, an integrated method comprising of GIS based MCDM and python has been employed to process and analyse spatial datasets in order to identify agricultural land, climatic suitability including water resources and productivity of wheat, rice, maize, and barley in the Aral Sea basin (Conrad *et al.*, 2016).

In order to enable estimation of the potential productivity of the different bioenergy feedstocks in this study, published studies for yield information on *Miscanthus x giganteus*, switchgrass, elephant grass and alfalfa were used (Table 6.1) This was done because there is limited or no biomass yield information available in any of the tropical African countries such as Mali, Ghana, Togo, Guinea, Senegal and Gambia). The productivity of alfalfa in the six Geopolitical zones of Nigeria was estimated by multiplying the yield in tonnes per hectare (t/ha) by the cell size of 9 (ha) to give a total productivity per cell. The results of these studies (Table 7.1) were selected due to similar climate of the studies to that of Nigeria. According to Behrman *et al.,* (2013) switchgrass yield was compared with a measured non-irrigated alfalfa yield obtained from the USDA-NRCS. The high yield of alfalfa indicated in Kayad *et al.,* (2016) as >5 t/ha was expressed in Behrman *et al.,* (2013) to have a range interval of 5 to 15 t/ha. It was on this premise that the average of the alfalfa high yield (>5) was taken as 10 t/ha. The average value was then multiplied by 9 ha to obtain 90 t/cell of land. This was calculated for both the medium and low yields to arrive at 41 and 18 tons/cell respectively. The total cell size (300 x 300) is equal to 90000 m^2 which is equivalent to 9ha, implying that 1 cell = 9 ha. The extracted yield information (t/ha) of land was further multiplied by the total hectares per cell to arrive at the yields per cell of land (Table 7.1).

Table 7.1: Productivity of the selected bioenergy species based on information gathered from the literature

Specie	High (t/ha)	Medium (t/ha)	Marginal (t/ha)	Low (t/ha)	Author & country
Miscanthus x giganteus 1	21-23 [22*9=**198**]	16-20 [18*9=**162**]	5.1-15[10*9=**90**]	1.1-5[3*9=**27**]	Mishra *et al.*, 2015 (Eastern, Central & Western, USA)
Miscanthus x giganteus 2	11.0*9=**99**	9.4*9=~**85**	—	7.7*9=**69**	Coffin *et al.*, 2016 (Southeastern, USA)
Switchgrass 1 (SG1)	23.5 *9=~**212**	15.5*9=~**140**	—	6*9=**54**	Coffin *et al.*, 2016 (Southeastern, USA)
Switchgrass 2 (SG2)	>18:18-20 [19*9=**171**]	10-18[14*9=**126**]	4-10 [7*9=**63**]	0.01-4.0 [2*9=**18**]	Behrman *et al.*, 2013 (Southern USA)
Elephant grass (EG)	30.1*9=**271**	19.7*9=**177.3**	—	7.1*9=**64**	Coffin *et al.*, 2016 (Southeastern, USA)
Alfalfa grass (AG)	>5:5-15[10*9=**90**]	4-5[4.5*9=~**41**]	2-4[3*9=**27**]	≤ 2[1*9=**18**]	Kayad *et al.*, 2016 (Saudi Arabia)

7.3 Productivity of alfalfa in Nigeria

For alfalfa (Fig 7.1a) the SW zone was indicated to possess a total productivity of about 58.3 million tonnes. This was an interesting zone since the poor production area contributed 7% and the suitable areas 92% to alfalfa production (Appendix 35). In the SS zone, alfalfa recorded a total productivity of 54.8 million tonnes with the poor areas producing 11% compared to 88% contribution from the suitable area. The SE zone had a total of 18.7 million tonnes where the poor production areas accounted for 13% while the high production locations produced 87% of total crop biomass (Fig 7.2; Appendix 35).

In the North, the NE zone was identified to produce the highest potential for alfalfa production with a total of 138.0 million tonnes (Fig 7.2). The poor areas contributed 23% of total production while the high productive areas accounted for 72% (Appendix 35). The NC zone had the second highest potential for alfalfa production, with a total of 130.3 million tonnes. The poor areas accounting for 18% of the total production while the high suitable location accounted for 81% (Appendix 35). In the NW, a total yield potential of 104.3 million tons was identified from the zone (Fig 7.2). About 25% of this was obtained from the low productive areas, while the high productive areas delivered 73% of the total.

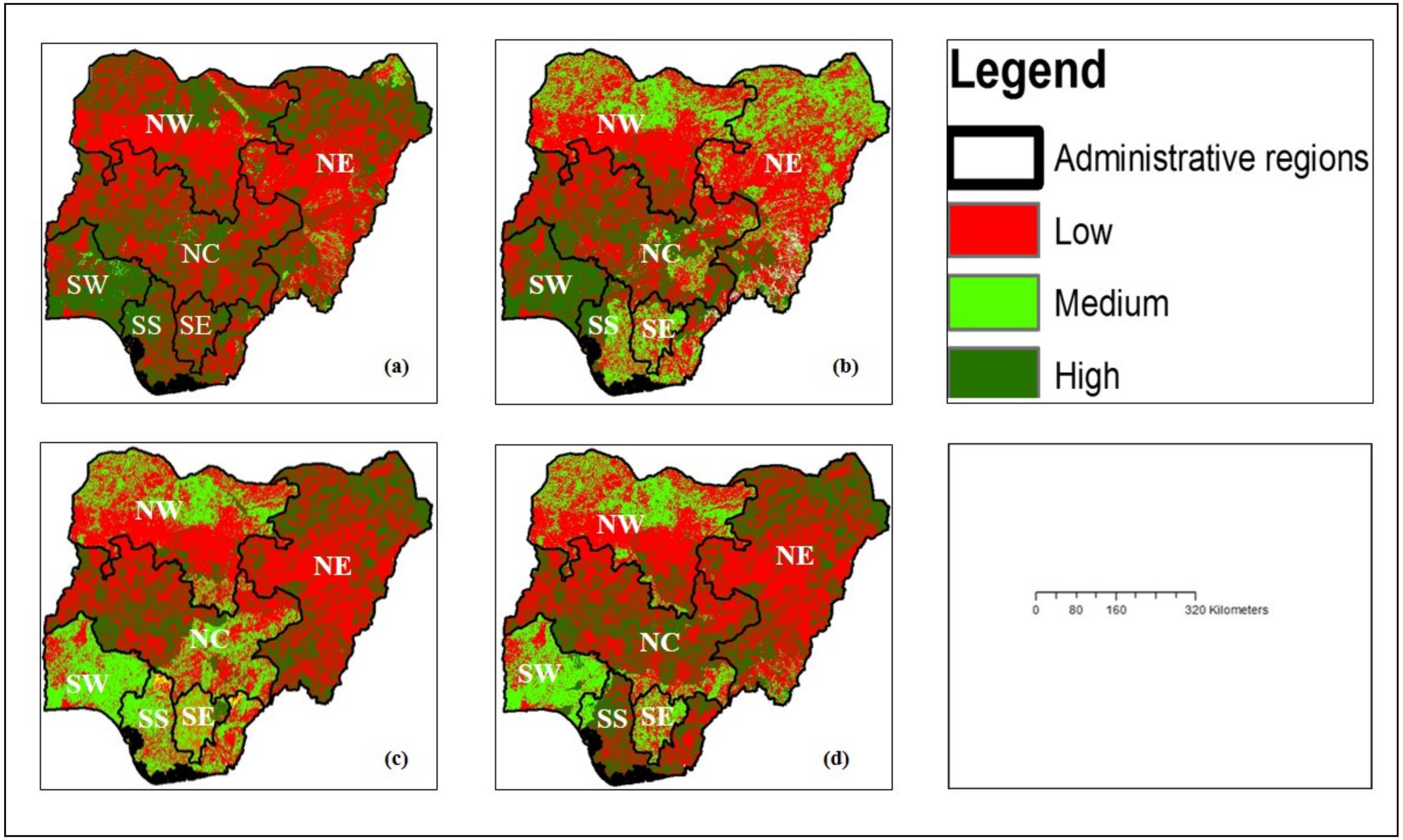

Figure 7.1: Evaluation of the productivity of a) Alfalfa, b) *Miscanthus x giganteus*, c) Elephant grass and d) Switchgrass across the six Geopolitical zones of Nigeria.

7.4 Productivity of Miscanthus x giganteus in Nigeria

For *Miscanthus x giganteus* (Fig 7.1b), the NE zone recorded the highest potential yield with about 300 million tonnes (Fig 7.2). The poor area produced about 16% of this while the highly productive areas accounted for 84% of total production in this zone (Appendix 36). The NC zone accounted for a total biomass production of 254 million tonnes (Fig 6.2), the poor areas accounting for about 14% while the medium and highly productive areas contributed 29% and 57% of total production respectively (Appendix 36). The NW zone accounted for a total potential production of 188 million tonnes (Fig 7.2). About 21% of the total biomass was obtained from the poor productive areas, 66% from the medium class whereas the highly productive area only contributed 13% of total production (Appendix 38). Further evaluation, revealed that the SE zone had the least production potential, where the zone recorded only 38.5 million tonnes (Fig 7.2). The poor area accounted for 9% of total production, the medium 13% while the high areas contributed 78% (Appendix 36). The SW zone was predicted to possess a total dry biomass production of 105.2 million tonnes (Fig 7.2). The potential of SW zone for the selected bioenergy feedstock was further revealed in *Miscanthus x giganteus* production, since the suitable areas classified as medium productive areas accounted for 94% of the total biomass while the poor area accounted for only 6% of the total biomass production (Appendix 36). The SS zone accounted for 99.6 million tonnes of total production (Fig 7.2), of which the suitable area accounted for 90% of the biomass while the poor locations represented only 9% of the total biomass (Appendix 36).

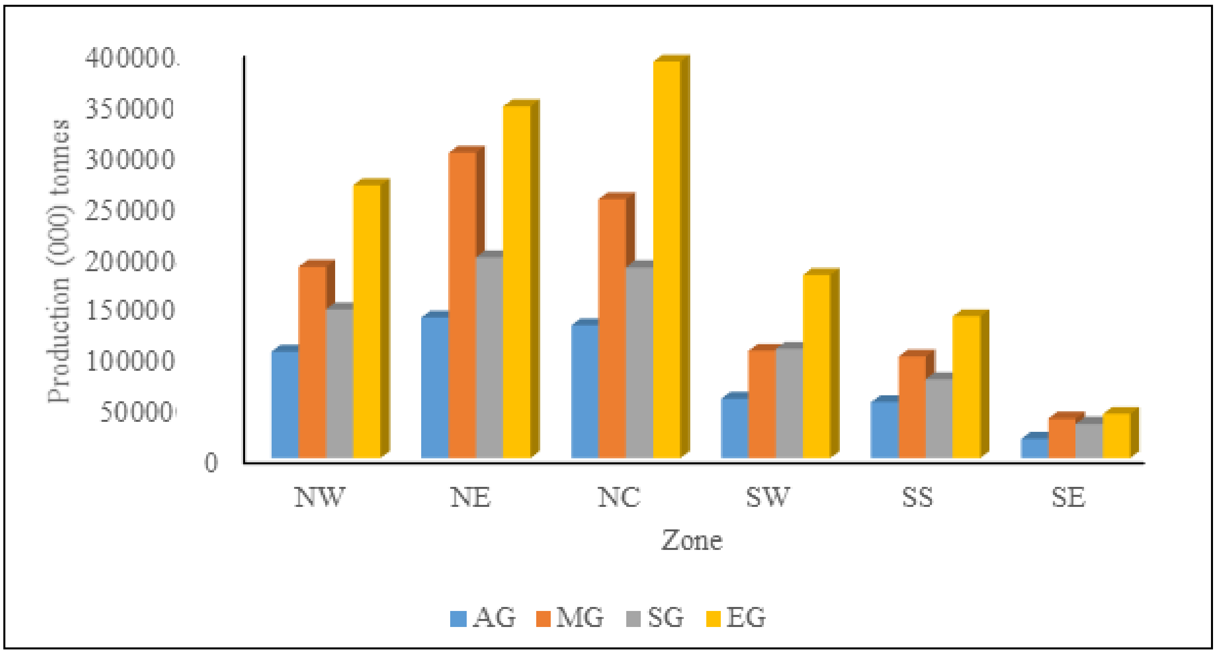

Figure 7.2: Estimated production of Alfalfa (AG), *Miscanthus x giganteus*, Elephant grass (EG) and Switchgrass (SG) in the six geopolitical zones of Nigeria

7.5 Switchgrass productivity

Results showed that the NE zone is predicted to produce about 197 million tonnes of switchgrass (Fig 7.16d; Fig 7.2). The poor areas contributed 16% while the suitable areas accounted for over 84% of total production. The NC zone recorded a total of 187.5 million tonnes. The poor suitable areas had 13%, the medium 59%, while the high suitable areas accounted for 28% of total crop biomass (Appendix 37). The NW zone possessed a total production of 146 million tonnes, where the poor suitable areas had 18%, the medium class 67% and the high productive areas 16% of total production (Appendix 37).

Generally, results of the productivity evaluation showed that Southern Nigeria possesses the least biomass production potential for switchgrass. In this respect, the SE zone was predicted to record a total of ~34 million tonnes (Fig 7.2). The areas identified with poor productivity accounted for only 7% while the highly suitable locations were predicted to produce 92% of the total crop (Appendix 37). The SS was further identified as the second least productive zone for switchgrass due to low suitable areas.

However, the SS zone recorded about 77.4 million tonnes of switchgrass biomass (Fig 7.2). The poor productivity areas accounted for only 8% while the suitable areas contributed 80% of the total production potential (Appendix 37). The SW zone had the production potential of 109.2 million tonnes of switchgrass (Fig 7.2), where the highly suitable areas accounted for 92% of the total biomass production (Appendix 37).

7.6 Elephant grass Productivity

Results predicted that NC is the most productive zone for growing elephant grass in Nigeria. A total productivity of 390 million tonnes was realized in the NC zone (Fig 7.1c; 7.2). The NE was second best with a total yield of 346 million tonnes (Fig 7.2). The poor productive areas accounting for 32%, the medium 55% and the high 13% of the total harvestable biomass across this zone (Appendix 38). The NW zone produced a total biomass of 268 million tonnes making it the third most productive zone for growing elephant grass in Nigeria. The poor areas accounted for 35%, the medium 47% while the high productive areas contributed 18% of total biomass production (Appendix 38). The SE zone was identified to produce a total DM yield of 43 million tonnes. About 20% was from the poor areas while 39% and 46% were produced from the medium and high productive locations respectively (Appendix 38). The SW exhibits the greatest potential for producing elephant grass in Southern Nigeria (Fig 7.1c). The zone recorded a total dry biomass yield of 180 million tonnes (Fig 7.2). The poor areas accounted for 7% of the production while the high productive land contributed over 92% of total production in the SW zone (Appendix 38).

7.7 Estimation of the most productive states in the North of Nigeria

Results of the productivity evaluation for alfalfa (AG) showed that Borno is the most productive state in the North Oyo state in the South (Fig 7.3a). Borno state recorded a total production of 38 million tonnes (Fig 7.4), where the poor suitable area accounted for 16% and the highly suitable areas accounted for 79% of total biomass production (Appendix 39).

Adamawa state was predicted to produce 13 million tonnes of alfalfa. The poor areas accounted for 37%, the medium areas 11% while the highly rated areas over 51%. Bauchi state produced 22.6 million tonnes, where the poor areas accounted for 28%, while the highly suitable areas accounting for 69% of total biomass production (Fig 7.4; Appendix 39). Taraba is the state second with highest potential for alfalfa production. The state recorded about 30 million tonnes (Fig 7.4), where the highly suitable areas accounted for 70% whereas the poor and medium rated classes contributed 20% and 8% of the total production respectively (Appendix 41). Yobe state accounted for 26 million tonnes while Gombe state had the least biomass production at 6 million tonnes (Fig 6.4), where the poor areas in Yobe state accounted for 18% of biomass while the highly suitable areas in Yobe contributed 82% of total alfalfa production (Appendix 39). In Gombe state, the poor areas accounted for 54% while the highly suitable areas with 41% of the total alfalfa production (Fig 6.4; Appendix 39).

7.8 Elephant grass productivity in the North

Borno state recorded the highest elephant grass production (Fig 7.3c), with about 88 million tonnes (Fig 7.4). The poor areas accounted for 26% of the production while the suitable areas accounted for 74% (Fig 7.4; Appendix 40). Taraba state accounted for 84 million tonnes, where the poor areas produced 24%, the medium 25% and the highly suitable areas ~50% of total production (Fig 7.4; Appendix 40). Like in alfalfa, Gombe state had the least production potential for elephant grass, the state had a total production of 16 million tonnes (Fig 7.4), while the poor and medium areas accounted for 66% and 34% of total biomass production (Appendix 40).

Yobe and Bauchi states had potential for 59 million tonnes and 57 million tonnes of elephant grass production each (Fig 6.4; Appendix 40), where the poor and high suitable areas in Yobe contributed 28% and 72% of the total biomass respectively. In Bauchi, the poor area accounted for 39%, while the suitable areas accounted for 61% of the total production respectively (Appendix 40). Adamawa state produced a total of 33 million tonnes of the crop, the poor area accounted for 47%, while the suitable areas contributed over 51% of the total biomass production (Fig 7.4; Appendix 40).

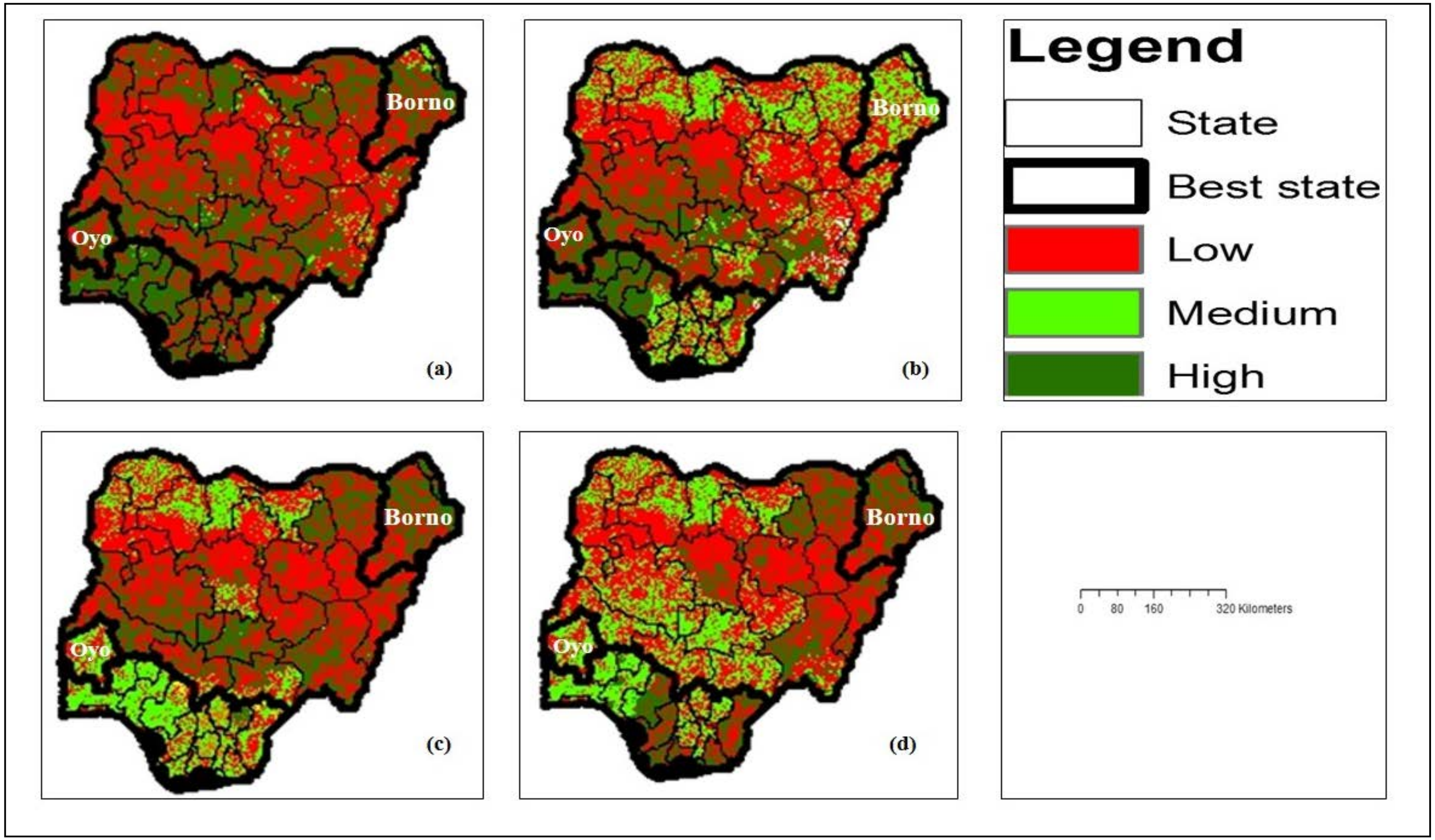

Figure 7.3: Evaluation of the most productive states for growing a) Alfalfa (AG), b) *Miscanthus x giganteus* c) Elephant grass (EG) and d) Switchgrass (SG) across Nigeria.

7.9 *Miscanthus x giganteus* productivity in the North

Borno state was identified as having the highest potential for *Miscanthus x giganteus* production. The state recorded a total production of 83 million tonnes, the poor areas accounted for 12% while the highly productive areas accounted for 88% of total biomass (Appendix 41; Fig 7.4). Taraba recorded the second highest potential for *Miscanthus x giganteus* with a total production of 69 million tonnes. The poor and highly productive areas accounted for about 14% and 86% of total harvestable biomass in the state (Appendix 41). Yobe accounted for 54 million tonnes while Bauchi had 47 million tonnes (Fig 7.4). In Yobe state, the poor area accounted for about 13% while the highly productive areas accounted for about 87%. In Bauchi state the poor areas accounted for 20% and the highly productive areas 80% of total production.

Adamawa state possessed a total production of 28 million tonnes, where the poor areas accounted for 25%, with the highly productive areas 74% of total biomass production.

Gombe is identified as the state with the least potential for growing almost all the bioenergy crops for biofuel production. The state recorded ~11 million tonnes of *Miscanthus x giganteus* (Fig 7.4), where the poor areas accounted for 42% and the highly productive areas 58% of the total production (Appendix 41).

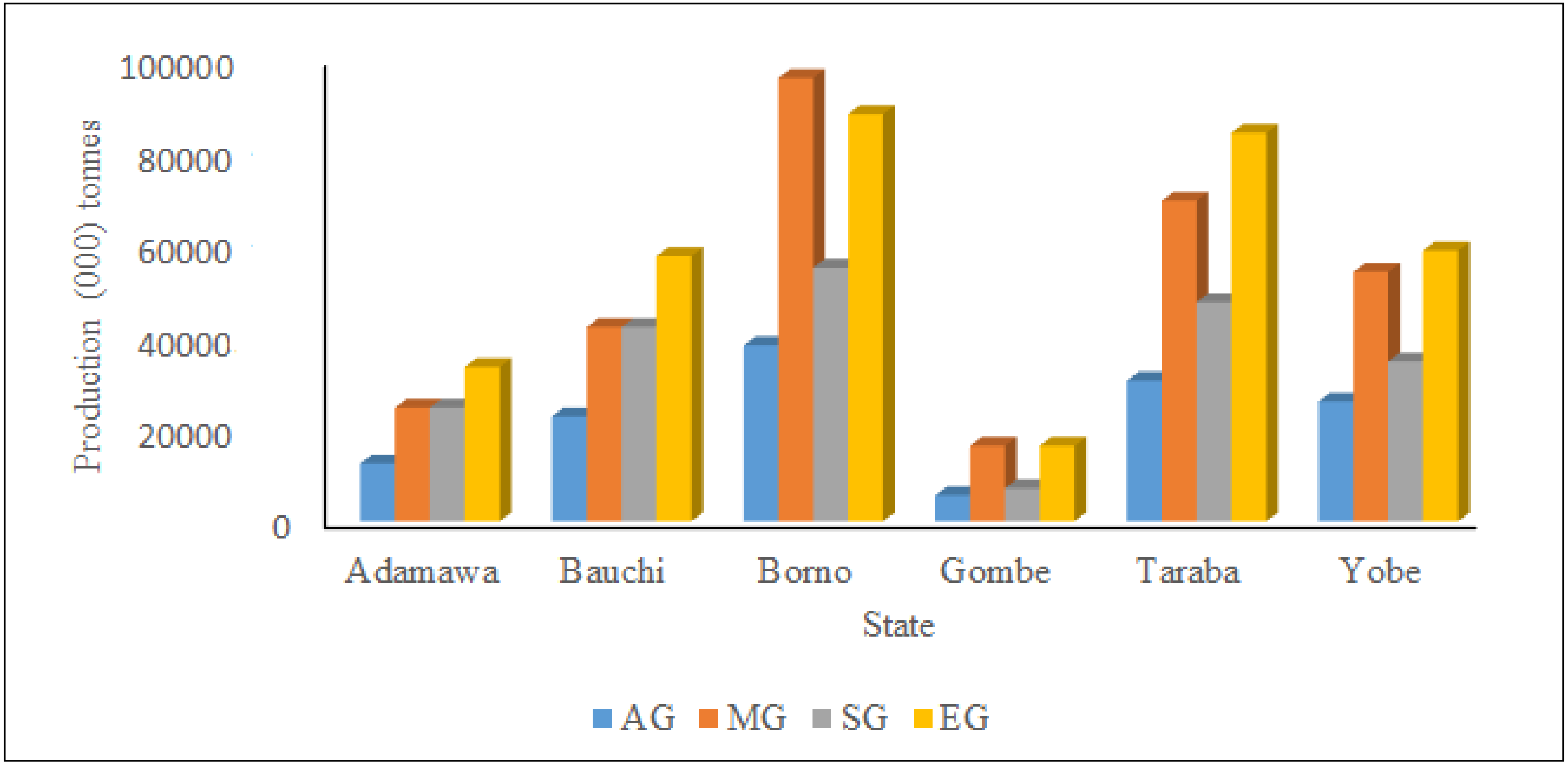

Figure 7.4: Production potential for bioenergy crops by states in the Northern Nigeria

7.10 Switchgrass productivity in the North

Results for switchgrass productivity showed that the crop is next to *Miscanthus x giganteus* in terms of potential feedstock for biofuel production in Nigeria (Fig 7.3b). Based on land area, Adamawa state recorded a total production of 25 million tonnes (Fig 7.4). About 19% of the total production was recovered from the poor area, with 81% identified from the highly suitable areas (Appendix 42).

Borno state recorded the highest potential with a total switchgrass production of 55 million tonnes, about 78% was produced from the suitable areas while the poor areas accounted for 12% of total production (Fig 6.4; Appendix 44). Taraba state recorded a total switchgrass production of 47 million tonnes while Yobe state accounted for 35 million tonnes (Fig 7.4; Appendix 42). In Taraba state, the poor areas accounted for 13% of the total production, the moderately suitable areas 68% while the highly suitable areas accounted for about 19% of total switchgrass production (Appendix 42). In Yobe state, the poor areas produced 13% while the highly suitable areas accounted for 86% of total biomass production (Appendix 42). Bauchi state is predicted to record a total production of 42 million tonnes (Fig 7.4), where the poor and highly productive locations accounted for 15% and 84% of the total biomass respectively (Appendix 44).

7.11 Alfalfa productivity in the South

Like in the North, alfalfa was identified as having the least potential for production in the South of Nigeria. According to the output information from the alfalfa productivity analysis, Oyo state is predicted to have the highest production potential for alfalfa. The state recorded about 19 million tonnes while Lagos state had the least potential with ~2 million tonnes (Fig 7.5). Oyo produced about 11% from the poor areas while 89% of the total production was recovered from the highly suitable areas. In Ekiti state, about 4% of the total biomass was realized from the poor areas while the suitable areas accounted for about 93% of total alfalfa biomass. Ondo state, recorded a total of 13 million tonnes, where the highly suitable areas accounted for over 96% of total alfalfa biomass. Ogun states had relatively similar biomass productivity with Ondo state of 13million tonnes with highly productive areas accounted for over 96% of the total biomass. Osun state accounted for ~8 million tonnes of alfalfa, where the highly suitable areas accounted for over 94% of total production (Fig 7.5; Appendix 43).

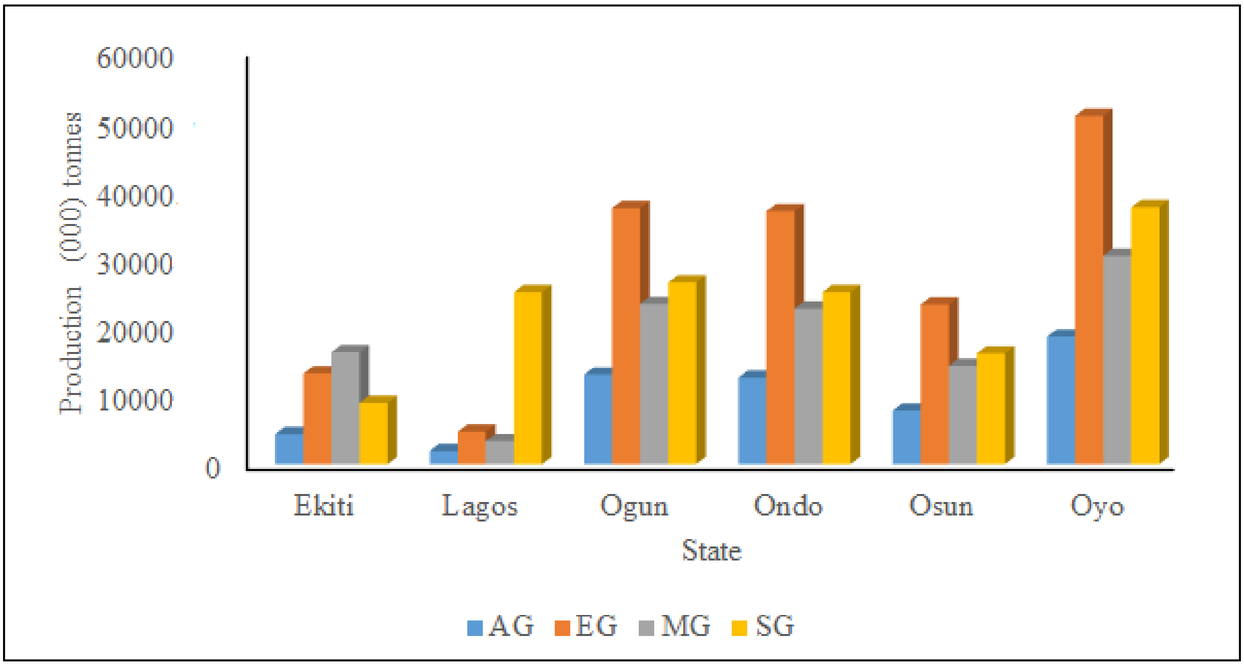

Figure 7.5: Production potential of bioenergy crop species by state in Southern Nigeria.

7.12 Elephant grass productivity in the South

In terms of elephant grass (EG) productivity, Oyo state had the highest potential in the South of Nigeria. The state recorded a total of 58 million tonnes, where the highly productive areas accounted for over 87% of total production (Appendix 44). Ondo and Ogun states recorded a total production of 38 million and ~40 million tonnes of total biomass respectively (Appendix 23; Fig 7.5). Ondo state had 96% and Ogun 94% of production from the highly production areas. Osun state possesses a total production of 24 million tonnes, where the highly productive areas accounted for over 95% of total production (Appendix 44). Ekiti state recorded a total of 14 million tonnes (Appendix 44) with the suitable areas accounting for 95% of total biomass production.

7.13 *Miscanthus x giganteus* productivity in the South

Oyo state recorded the highest potential for *Miscanthus x giganteus* in the South of Nigeria. The state accounted for 33 million tonnes of total production (Fig 7.5; Appendix 45). With the suitable areas contributing 93% of total biomass. Lagos was the least productive state with a total production of 3.4 million tonnes (Fig 7.5). Ogun state had a total production of 23.3 million tonnes, where the suitable areas contributed over 95% of total biomass (Appendix 45).

Ondo state had a total *Miscanthus x giganteus* production of 23 million tonnes, where 96% of total biomass production came from the suitable areas. Osun state recorded a total biomass of 14 million tonnes where the low productive areas accounted for 3%, while the suitable areas recorded 96% tonnes of total biomass production (Fig 7.5; Appendix 45).

7.14 Switchgrass productivity in the South of Nigeria

Results for switchgrass productivity indicated that Oyo is another highly productive state for switchgrass in the South. The state recorded a total production of 37 million tonnes (Fig 7.5), where the highly suitable areas accounted for over 94%, of total production (Appendix 46). Ekiti state recorded the least switchgrass production with about 9 million tonnes (Fig 7.5), although 88% of this was from the highly suitable areas (Appendix 46). Lagos state recorded a total of 25 million tonnes with 90% of the total production obtained from the highly suitable areas and with only 2% of total potential biomass from poor areas. Ogun and Ondo states recorded similar totals of 26 and 25 million tonnes respectively (Fig 7.5), with the highly productive areas accounting for 90% of potential production in both states.

Osun state had a total switchgrass production potential of 16 million tonnes, where the highly productive land accounted for about 94% of total biomass (Appendix 46; Fig 7.5).

7.15: A sensitivity analysis of the model parameter

Sensitivity analysis (SA) was carried out on the estimated biomass yield of the species at ±20% of the literature-based yield parameters. Results for the south of Nigeria, showed that there were significant changes on the individual outputs of the species as the moderately high yield parameters increase (Appendix 65).

For instance, in the SW zone, results of the sensitivity analysis for alfalfa productivity showed that at 20% yield increase, there was a significant change (120 million tonnes) from the estimated (767 million tonnes) compared to the original yield of 647 million tonnes of biomass (Appendix 65). Also, at 20% decrease in yield of the species, results of the sensitivity analysis showed a significant change of about 349 million tonnes compared to the primary output (647 million tonnes of the species) (Appendix 65).

Results of the sensitivity analysis also showed a significant change (8.6 million) in yield of alfalfa biomass in the NE zone. The species was identified to record an increasing difference of about 1.3 million tonnes compared to the original model output (Appendix 65). It was further indicated that a 20% decrease of the input parameter, that there was a significant reduction on the biomass yield of the species (Appendix 65).

In terms of *Miscanthus x giganteus* (MG), results of the analysis sensitivity analysis at ±20% for moderately high yield parameters, showed that the SW zone has a tremendous change in the model output with a difference of 20 million tonnes of the species (Appendix 65) compared to the 99.2 million tonnes obtained from the previous estimation (Appendix 34).

For the NE zone, it was also identified that by increasing the model parameter, results showed that there would be a slight difference of about 10 thousand tonnes of the species compared to the original output (Appendix 65 and 34).

However, based on the estimations, it was shown that significant changes occurred in the model outputs of both switchgrass and elephant grass (Appendix 65).

Chapter 8: Estimation of Cellulosic Bioethanol Production and Potential Biorefineries in Nigeria.

Glucose content of the 4 species was used to determine bioethanol potential with values extracted from the literature used to estimate ethanol yield. The glucose contents labelled glucose 1 and 2 implied values obtained from two separate studies to enable us compare the yields and come up with an average value of the two datasets (Table 8.1).

In order to enable this estimation, equation 5 was used;

Ethanol yield (L) = Biomass resource amount (kg) X Glucose content

X Fermentation efficiency (85%)

X Theoretical ethanol yield (51%)

X Process recovery (90%)/ Specific gravity of ethanol 0.79 (kg/l)

(Iye and Bilsborrow 2013a).

8.1 Validation of the ethanol yields

The ethanol production potential was validated from the estimated yield of switchgrass biomass based on 5.4 grams (g) of ethanol per 100 grams of pre-treated switchgrass biomass (Luque *et al.,* 2016). The value gave 0.068 litres per kilograms (l/kg) which is relatively higher than the 0.030 l/kg used in this study. The result was used for validation since the ethanol yield was based on glucose content. However, the high ethanol yield was attributed to the increasing rate of acetic acid used for the pre-treatment of the sample which was carried out under anaerobic conditions. Also, the increase in reaction time was another factor that contributed to the high yield.

The ethanol production of *Miscanthus x giganteus* of 13 grams per 100grams (0.130 l/kg) of raw *Miscanthus x giganteus* when converted is 0.164 l/kg (Lee and Kuan., 2015). This was higher than the 0.0307 l/kg used in this study. The high yield was as a result of the conversion processes used in the literature, where the pre-treatment methods and conditions involved liquid hot water (LHW) or alkaline employed to obtain the glucose content and the ethanol conversion carried out at 200°C within a reaction time of 10 min. Another factor that was considered to have caused these high ethanol yields was the different climatic conditions where the crops were grown.

In terms of ethanol yield from alfalfa and elephant grass, there is currently limited information in the literature. However, based on these constraints, this study recommends for future study to use a laboratory based method to determine the ethanol production rates of these energy crops to compare with the estimated results.

Table 8.1: Glucose composition (%) of lignocellulosic bioenergy crops for cellulosic bioethanol estimation.

Component (%)	**Glucose 1**	**Glucose 2**	**Average glucose %**	**Reference**
Switchgrass	38.8	43.7	41.3	Hu *et al.*, 2010; David and Ragausk, 2010
Miscanthus x giganteus	48.4	49.5	49.0	Vandergham *et al.*, 2010; Huyen *et al.*, 2010
Elephant grass	57.8	50.3	50.6	Bensah, 2015; Rengsirikul *et al.*, 2013
Alfalfa	67.5	57.0	62.3	Dien *et al.*, 2011; Duceppe *et al.*, 2012

The ethanol yield and number of processing facilities (biorefineries) were determined based on the estimated biomass production in this study. According to Berntsson *et al.* (2012) *a* biorefinery is a processing facility that provides sustainable processing of biomass resources into diverse spectrum of marketable products and energy. A biorefinery utilizes different kinds of biomass such as agricultural residues, purposely grown bioenergy crops as well as aquatic biomass such as algae (De Jong and Jungmeier, 2015).

The capacities of potential large commercial biorefineries to be established in Nigeria was adopted (Sokhansanj *et al.*, 2009), which defined a large scale biorefinery as one that possess a biomass input potential of 500–5000 dry tonnes per day while the medium scale possess a dry biomass input capacity of at least 2000 tonnes per day. Since an ideal large commercial biorefinery was indicated to possess at least a capacity of 5000 tonnes/day which is equivalent to 1.8 million tonnes per annum. Crop productivity was divided by the plant input capacity to determine the potential for large commercial biorefineries in each Geopolitical zone.

8.2 Evaluation of alfalfa for bioethanol production and potential biorefineries required in each zone

Based on a single feedstock only production facility, the NE was identified to possess the highest potential. The zone had the potential to produce 42.3 billion litres of cellulosic bioethanol per annum based on 100% utilization of the area. The estimated output was indicated to support 76 large scale biorefineries to use the 138 million tonnes of alfalfa biomass (Table 8.2). The NC zone is second with ~40 billion litres of cellulosic bioethanol produced, from 71 large scale facilities converting 130 million tonnes of alfalfa. The NW zone had a total alfalfa productivity of 104 million tonnes, accounting for 32 billion litres of cellulosic ethanol from 57 large processing facilities (Table 8.2). Across Southern Nigeria, the SW zone was predicted as the most productive location while the SE geopolitical zone was the least productive zone. The SW zone was predicted to have the capacity of employing 32 large processing facilities to convert 58.3 million tonnes of alfalfa and produce 17.9 billion litres of cellulosic ethanol per annum. For the SE Geopolitical zone providing 18 million tonnes of alfalfa would produce about 5.8 billion litres of cellulosic bioethanol per annum with 10 large scale commercial facilities.

8.3 Evaluation of *Miscanthus x giganteus* for bioethanol production and potential biorefineries required in each zone

The NE zone recorded the highest potential in terms of *Miscanthus x giganteus* as a single feedstock. The zone was indicated to require 164 large scale facilities to convert 300 million tonnes of dry biomass and produce 73 billion litres per annum. The NC was indicated as having the second highest potential zone for cellulosic ethanol production in the Northern region requiring 139 large commercial processing biorefineries to convert 254 million tonnes of dry biomass to 61 billion litres of cellulosic ethanol per annum. The NW zone with 188 million tonnes of *Miscanthus x giganteus* dry biomass would produce about 45 billion litres of bioethanol from 103 large biorefineries. In the South, SW zone with 89.7 million tonnes of dry *Miscanthus x giganteus* accounted for about 22 billion litres of ethanol per annum with a total estimation of 49 large scale commercial biorefineries. The SE zone had the least production potential, the zone would need 16 large scale biorefineries to enable the conversion of 19 million tonnes of dry biomass, to generate 7 billion litres of cellulosic ethanol per annum (Table 8.2).

8.4 Evaluation of switchgrass for bioethanol production and potential biorefineries required in each zone

In terms of switchgrass, the NE zone had the highest potential with a total of 48 billion litres of cellulosic bioethanol per annum. The output capacity was predicted to require 129 large scale commercial biorefineries to convert 235 million tonnes of dry switchgrass. In the NC zone, 112 large scale commercial biorefineries would be required to convert 204 million tonnes of switchgrass dry matter to produce 41 billion litres of cellulosic bioethanol per annum. The NW was predicted to produce 24 billion litres of cellulosic ethanol from 117 million tonnes of switchgrass dry biomass with 64 large scale commercial biorefineries required.

In the Southern region, the SW recorded the highest ethanol productivity with about 12 billion litres of switchgrass biomass, requiring construction of 34 large scale commercial biorefineries. The SS zone was indicated to have the potential for 18 billion litres of cellulosic ethanol per annum, requiring 90.8 million tonnes of dry switchgrass for 50 large scale commercial biorefineries. The SE zone with the least ethanol production potential across the entire country with only 16 large scale biorefinery facilities to enable the conversion of 18.8 million tonnes of switchgrass to 4 billion litres of cellulosic bioethanol (Table 8.2).

8.5 Evaluation of Elephant grass for bioethanol production and potential biorefineries required in each zone

In respect to the conversion of elephant grass to cellulosic ethanol, the NC zone was predicted to have the highest potential with 98 billion litres of cellulosic bioethanol, requiring 214 large scale facilities converting 390 million tonnes of biomass. The NE was the second most productive zone in the North which would require 176 large facilities, to enable conversion of

322 million tonnes of biomass to 81 billion litres of cellulosic bioethanol per annum (Table 8.2). In the Southern region, the SW zone could produce 45 billion litres of ethanol per annum, having 99 large scale biorefineries to convert 180 million tonnes of feedstock. The SS recorded could produce 35 billion litres while the SE has the least potential across Nigeria for biofuel development with a total estimation of 11 billion litres of cellulosic bioethanol per annum. The zone was predicted to require 24 large scale biorefineries to enable use of 43 million tonnes of switchgrass per annum. Also, the SS zone on the other hand was predicted to require 76 large scale facilities to enable the conversion of 139 million tonnes of elephant grass to 33 billion litres of cellulosic bioethanol (Table 8.2).

Table 8.2: Estimation of cellulosic bioethanol production (Billion litres) from Alfalfa grass (AG), *Miscanthus x giganteus* (MG) Switch grass (SG) and Elephant grass (EG) and number of processing facilities required in each zone.

ZONE	AG (000 tonne)	Ethanol yield (Bl)	N° of processing facilities	MG (000 tonne)	Ethanol yield (Bl)	N° of processing facilities	SG (000 tonne)	Ethanol yield (Bl)	N° of processing facilities	EG (000 tonne)	Ethanol yield (Bl)	N° of processing facilities
NW	104347	31.95	57	188000	45	103	117000	24	64	268000	68	147
NE	138035	42.27	76	300000	73	164	235000	48	129	322000	81	176
NC	130281	39.89	71	254000	61	139	204000	41	112	390000	98	214
SW	58317	17.86	32	89754	22	49	61486	12	34	180000	45	99
SS	54890	16.81	30	113000	27	62	90781	18	50	139000	35	76
SE	18781	5.75	10	29672	7	16	18782	4	10	43140	11	24

8.6: Sensitivity analysis of ethanol yield potential

In terms of the sensitivity analysis carried out on ethanol productivity at ±20% of the model parameter, results of the analysis showed a significant change in the ethanol productivity of alfalfa biomass in the six geopolitical zones (Appendix 66).

However, at the increasing end (+20%) of the model parameters, results showed a significant increase (8.9 million litres of cellulosic ethanol), i.e. from 42.3 to 51 million litres and a decrease of 8.18 million litres of cellulosic ethanol in the NE zone (Appendix 66).

In the south, the estimation results showed an increase of 4 million litres of ethanol from alfalfa biomass (Appendix 66). Further changes were indicated on the model output, when the parameters were adjusted on the basis of a ±20% yield of ethanol from *Miscanthus x giganteus* biomass (Appendix 66 and 67). The sensitivity analysis results then showed that the rate of ethanol production would potentially increase by about 15 and 4.4 million litres of ethanol from the species in the NE and SW zones respectively. It was also gathered that switchgrass and elephant grass would have significant effect to the ethanol productivity in the zones, if the further adjustments are made on the model parameters. For instance, the SW zone was identified to increase by 11 and 16 million litres respectively (Appendix 66) on increasing the yield parameters by ±20%.

8.6 Evaluating the potential of cellulosic bioethanol production and potential biorefineries by individual states in the North

This was further developed by looking at the potential number of large processing facilities in each state.

For alfalfa, Borno state was predicted to have the highest potential for construction of 22 large scale processing facilities, converting 41 million tonnes of alfalfa into 12.5 billion litres of cellulosic bioethanol per annum (Table 8.3). Taraba state was indicated as having the second highest potential requiring 17 large scale commercial biorefineries to convert 30.4 million tonnes of alfalfa to 9 billion litres of cellulosic bioethanol. Gombe state recorded the least potential for cellulosic bioethanol in the Northern region with only 1.7 billion litres per annum (Table 8.3), with the potential for 3 large scale biorefineries to enable the conversion of 5.6 million tonnes of alfalfa.

For *Miscanthus x giganteus,* Borno state has the highest potential with 53 large scale biorefineries to enable the conversion for 96 million tonnes of feedstocks to 23.2 billion litres of cellulosic bioethanol per annum. Taraba state was the second highest state with a total ethanol production of 20.3 billion litres of ethanol per annum, requiring 46 large scale commercial facilities (Table 8.3).

Gombe state was again indicated as having the least potential in the Northern region for this species with the potential for 4 billion litres of cellulosic bioethanol and the capacity for 9 large scale commercial biorefineries.

For switchgrass as a single feedstock for conversion to cellulosic bioethanol in the Northern region, Borno state had the highest potential for ethanol production. The state has the capacity for 50 large scale biorefineries with the capacity to produce 18.4 billion litres of cellulosic bioethanol. Taraba is the second most productive state, with the potential for over 14 billion litres of cellulosic bioethanol per annum, having the potential for 38 large scale biorefineries. Gombe had again the lowest potential with only 2.2 billion litres (Table 8.3).

For elephant grass as a single feedstock for cellulosic bioethanol production in the Northern region, Borno state had the highest potential. The state accounted for 15.5 billion litres of cellulosic bioethanol per annum, which would require 34 large scale facilities. Taraba had the second highest potential for biofuel production, with the potential to produce 11.9 billion litres per annum while Gombe state only had the potential for 1.8 billion litres of cellulosic ethanol per annum (Table 8.3).

Table 8.3: Estimation of cellulosic bioethanol production (Billion litres; Bl) from Alfalfa grass (AG), *Miscanthus x giganteus* (MG) Switch grass (SG) and Elephant grass (EG) and the number of processing facilities required in individual states in the Northern Nigeria.

State	AG (tonnes)	Ethanol (Bl)	Nº of processing facilities	MG (tonnes)	Ethanol (Bl)	Nº of processing facilities	SG (tonnes)	Ethanol (Bl)	Nº of processing facilities	EG (tonnes)	Ethanol (Bl)	Nº of processing facilities
Adamawa	12537939	3.8	7	33421433	8.1	18	28060164	5.7	15	24607440	6.2	13
Bauchi	22680709	6.9	12	57405472	13.9	31	47052540	9.5	26	42032349	10.6	23
Borno	40797521	12.5	22	96015128	23.2	53	90984006	18.4	50	61348284	15.5	34
Gombe	5625059	1.7	3	16360459	4.0	9	10989036	2.2	6	7131924	1.8	4
Taraba	30459572	9.3	17	84068810	20.3	46	69395040	14.1	38	47410515	11.9	26
Yobe	25933508	7.9	14	58628449	14.2	32	53969085	10.9	30	34574553	8.7	19

8.7 Evaluating the potential of cellulosic bioethanol production and number of processing facilities by individual states in the South of Nigeria

For alfalfa, Oyo state had the highest potential with 5.7 billion litres of cellulosic bioethanol per annum, which would require 10 large scale facilities to utilize the 19 million tonnes of alfalfa. Ogun state would require 7 large scale facilities to allow a conversion of 13 million tonnes of alfalfa to 4 billion litres of ethanol per annum (Table 8.4). Lagos state was indicated to possess the least potential; for cellulosic ethanol production in the South of Nigeria state with the potential for only 1 large scale biorefinery requiring 1.9 million tonnes of alfalfa feedstock and producing 500 million (0.6 billion) litres of cellulosic bioethanol (Table 8.4).

For elephant grass, results of the ethanol productivity indicated that Oyo state has the highest potential with 18.5 million tonnes of production, requiring 10 large scale biorefineries with an output of 5.7 billion litres of cellulosic bioethanol per annum (Table 8.4). Ogun and Ondo states had similar potential for bioethanol production at 9.4 and 9.3 billion litres per annum respectively, requiring 20 large scale processing facilities. Lagos state has the lowest potential with only 1.2 billion litres of cellulosic bioethanol per annum, requiring 3 large scale processing facilities.

For *Miscanthus x giganteus* in the Southern region, Oyo state has the highest potential. The state would require 17 large scale facilities to produce 7.4 billion litres of ethanol per annum. Also in this context, Ogun and Ondo states were rated as the second highest potential for cellulosic bioethanol in the South of Nigeria. The states recorded 5.6 and 5.5 billion litres of ethanol per annum respectively, requiring 13 -12 large scale facilities respectively (Table 8.4).

Lagos state has the least potential with the requirement for only 2 large scale biorefineries to produce 800 million (0.8 billion) litres of ethanol per annum (Table 8.4).

For switchgrass, Oyo state again was indicated to possess the highest potential in the South, with the capacity for 21 large scale facilities to convert 34 million tonnes of switchgrass to 7.6 billion litres of ethanol per annum. Ogun and Ondo states accounted for 5.36 and 5.07 billion litres of cellulosic bioethanol respectively, each requiring 14 large scale facilities. According to the evaluations, Lagos state had the least potentials with 700 million (0.7 billion) litres of cellulosic ethanol per annum. The state would only require 2 large scale biorefineries in order to effectively convert the available biomass in the state (Table 7.4).

Table 8.4: Estimation of cellulosic bioethanol production (Billion litres; Bl) from Alfalfa grass (AG), Miscanthus x giganteus (MG) Switch grass (SG) and Elephant grass (EG) and number of processing facilities required in individual states in the Southern Nigeria.

State	AG (tonnes)	Ethanol (Bl)	Nº of processing facilities	EG (tonnes)	Ethanol (Bl)	Nº of processing facilities	MG (tonnes)	Ethanol (Bl)	Nº of processing facilities	SG (tonnes)	Ethanol (Bl)	Nº of processing facilities
Ekiti	4386411	1.3	2	13218744	3.3	7	16304436	3.9	9	8949762	1.81	5
Lagos	1922778	0.6	1	4751985	1.2	3	3354993	0.8	2	3635496	0.74	2
Ogun	13037396	4.0	7	37290955	9.4	20	23296725	5.6	13	26461386	5.36	14
Ondo	12588315	3.9	7	36817518	9.3	20	22637250	5.5	12	25033113	5.07	14
Osun	7811513	2.4	4	23235695	5.9	13	14329710	3.5	8	16145685	3.27	9
Oyo	18568824	5.7	10	50693245	12.8	28	30311496	7.3	17	37414530	7.58	21

8.8 Evaluating the potential of single feedstock in Nigeria based on 100% utilization of the country's suitable grassland and shrubland.

The entire evaluation of the theoretical ethanol yield at the zonal level was based on 100% utilization of the study area. Though all the C4 species were indicated with significant potential, but elephant grass accounted for the highest potential nationally with 338 billion litres per annum and 735 processing facilities. *Miscanthus x giganteus* was second highest potential species with 236 billion litres per annum and 534 processing facilities. Alfalfa accounted for 155 billion litres and 277 processing facilities, while switchgrass has the least potential with 147 billion litres and 389 large processing facilities (Table 8.5).

Therefore at 100% utilization of the suitable land, the study showed that Nigeria could produce about 876 billion litres of cellulosic ethanol per annum (Table 8.5).

Table: 8.5: Evaluating the potential of single feedstock in Nigeria based on 100% utilization of the country's suitable grassland and shrub land.

Species	Biomass ('000 tonnes)	Ethanol yield (Bl)	No of Processing facilities
Alfalfa (AG)	504,652	155	277
Miscanthus x giganteus (MG)	974,426	236	534
Switchgrass (SG)	727,049	147	389
Elephant grass (EG)	1,342,140	338	735
Total	**3,548,266**	**876**	**1935**

8.9 Evaluating the potential for grassland and shrubland utilisation based on current livestock numbers in Nigeria

The previous information has shown the potential need for a significant number of large scale commercial processing facilities in each geopolitical zone of Nigeria based on 100% use of the grassland and shrubland areas. This estimation would eliminate all the current livestock in the country, and was assumed not to be feasible. As livestock are extensively grazed on grassland and shrubland in Nigeria it is important to identify what proportion of current land is utilised for this purpose. This would then enable a clearer picture of the amount of land potentially available for biofuel production not competing with current uses. This would in essence enable decision makers consider and avoid possible feed versus fuel conflict that may arise in the nation's energy and agricultural sub sectors if the current Biofuel Policy is implemented without considering other requirement and uses. Information on the population and stocking densities of cattle, goat and sheep across the country was based on National Statistics figures. The area for livestock production was deducted from the total grazing areas (grassland and shrubland) in each zone to obtain a more accurate estimation of the potential available land for bioenergy crop production (Table 8.9).

To enable the evaluation, the average total population of the small ruminants (i.e. goats and sheep) from 2011 to 2013 obtained from the Federal Department of Animal Production & Animal Husbandry Services, Nigeria (2014) were summed and then divided by the average stocking densities (11 and 18 head per hectare for the south and north of Nigeria respectively); defined as the maximum number of livestock that can be sustainably supported by a given area of pastureland was obtained from the literature based information (Onifade *et al.,* 2002) and expert opinions from the Animal Science department of Ebonyi State University (Appendix

51-53). Also the average population of cattle from 2011 to 2013 was divided by the stocking density (6 and 7 head per hectare) (Appendix 51) to obtain area for cattle production in the south and North (Onifade *et al.*, 1988). Therefore, the area for small ruminant and cattle were summed together to estimate the potential area required for livestock production in each state and zone of Nigeria (Table 8.6).

Based on the estimation, Northern Nigeria had a significantly higher number of livestock compared to the South. The North recorded a total of 95 million while the South had only 23 million head, where the NW zone alone was identified to possess over 50% of the country's livestock population. The zone recorded 57 million head while the SE had only 5.2 million head (Table 8.6).

Table 8.6: Population of livestock (cattle, sheep and goat) in each zone

Zone	Population of sheep	Population of goat	Population of cattle	Total population	area for small ruminant	area for cattle	Area for livestock
NW	23,129,581	24,111,781	10067851	57,309,213	25,321,561	1,677,975	26,999,536
NE	6,603,820	8,134,410	5270614	20,008844	7,343,312	878,436	8,221,748
NC	5,702,809	6,716,436	5527623	17,946,868	6,313,394	921,271	7,234,665
SE	708,978	4,512,678	15849	5,237,504	1,119,221	2,641	1,121,863
SS	856,966	4,772,850	152782	5,782,598	1,290,862	25,464	1,316,325
SW	1,524644	10,371,584	139568	12,035,796	2,467,515	23,261	2,490,776
Country	Overall total			118,320,823			47,384,913

In terms of livestock population by state in the North, Borno state had the highest population of livestock with about 6.2 million, with 1.7 million head of cattle as well as 2.2 and 2.3 million head of sheep and goats respectively.

Adamawa state was second highest with 4 million head, the state possessed 1.5 million goats while cattle and sheep accounted for 1.1 and 1.4 million head respectively. Bauchi state was found to record the least livestock production with a total population number of 1.1 million head with 541,367 head of cattle, 361,129 goats and 208,935 sheep (Table 8.7).

Table 8.7: Average population of livestock (cattle, sheep and goat) by states in the Nor.

State	Average population of cattle	Average population of goat	Average population of sheep	Total population of livestock
Adamawa	1,141,756	1,561,692	1,386,360	4,089,808
Taraba	302,336	951,377	960,341	2,214,054
Yobe	1,008,840	1,835,908	1,216,646	4,061,395
Gombe	549,651	1,146,325	596,682	2,292,658
Bauchi	541,367	361,129	208,935	1,111,431
Borno	1,726,664	2,277,978	2,234,856	6,239,498

Though there was no record of cattle production in Osun state, the state had the highest number of livestock (small ruminants) in the South with over 4 million head. Oyo state was second with an average population of 3.5 million head, the state has over 2.8 million head of goats. Ekiti and Ogun state have relatively similar populations of livestock with 1.0 and 1.1 million head respectively. Lagos state has the least livestock population with only 10 thousand head of goats while there was no record of cattle and sheep in the state (Table 8.8).

Table 8.8: Average population of livestock (cattle, sheep and goat) by states in the South from 2011 – 2013.

	Average population of cattle	Average population of goat	Average population of sheep	Average total population
Ekiti	32,930	909,003	60,740	1,002,675
Ogun	14,065	935,024	168,113	1,117,204
Ondo	34,276	2,176,479	136,871	2,347,627
Osun	0	3,506,092	562,062	4,068,154
Oyo	58,294	2,834,329	596,856	3,489,480
Lagos	0	10,655	0	10,655

8.10 Evaluating the land availability for cellulosic bioethanol based on livestock population in each zone.

The NW zone has the highest livestock population in Nigeria with over 50% of the total country's population (Table 8.6). Based on the estimations, the NW zone was identified to have 4.1 million ha available for livestock production from the total suitable land in the area (Table 8.6).

The NE zone being considered previously as the Zone with the highest potential based on total suitable land area, was found to have the second highest livestock population with over 20 million head (Table 8.6). The zone was estimated to require about 8.2 million ha based on a sustainable stocking rate resulting in 3.3 million ha being available for biofuel production (Table 8.9). Based on the 28% of the total suitable area for biofuel production, it was indicated that the NE zone has the potential for 9 processing facilities using 16.4 million tonnes of alfalfa biomass and produce 504 million litres of cellulosic ethanol. The NC zone has the potential for 11 processing facilities using 20 million tonnes of alfalfa biomass, to produce 607 million litres of cellulosic ethanol (Table 8.6 and 8.9).

In the South, it was indicated that out of the 23 million head of cattle in the region, the SW alone accounts for over half of this population (i.e. 12 million head). Based on livestock population, the zone was identified to require 2.5 million ha to support its livestock production. Based on the evaluation, the SS zone was indicated to possess the highest potential for biofuel production (Table 8.6). The zone with the potential to produce 25 million tonnes of alfalfa biomass would require 14 processing facilities to produce 767 million litres of cellulosic ethanol. The SW has the second highest potential with 24 million tonnes of biomass feeding 13 facilities to produce 724 million litres of ethanol (Table 8.9). The SE zone has the lowest potential, requiring only 2 processing facilities to convert 3.4 million tonnes of alfalfa biomass to 104 million litres of cellulosic bioethanol (Table 8.6 and 8.9).

The SW zone was identified to have the highest potential for bioethanol production from elephant grass. The zone could produce 73 million tonnes of biomass to feed 40 processing facilities and produce 2.2 billion litres of ethanol. The SS zone has the potential for ~2 billion litres of cellulosic ethanol and 35 facilities, while the SE zone has the lowest potential producing 8 million tonnes of biomass which would feed 5 facilities and produce 240 million litres of cellulosic ethanol (Table 8.9).

In Northern Nigeria, the NC zone was identified with the potential to produce 59 million tonnes of elephant grass to feed 32 facilities and produce about 1.2 billion litres of ethanol (Table 8.9).

For *Miscanthus x giganteus* evaluation, the SS zone has the potential for 1.4 billion litres cellulosic ethanol per annum from 25 processing facilities while the SW and NC zones each can produce 42 and 39 million tonnes of biomass to feed 23 and 21 processing facilities and produce 1.3 and 1.2 billion litres of cellulosic ethanol respectively (Table 8.9).

For switchgrass, the SW zone was able to produce 1.3 billion litres, the SS 1.1 billion litres and NC zone 876 million litres of cellulosic ethanol. The SW zone has the potential for 43.3 million tonnes of biomass to feed 24 processing facilities. The SS would require 19 processing facilities to convert 35.2 million tonnes of biomass while the NC zone has the potential to produce 29 million tonnes of switchgrass to feed 16 processing facilities (Table 8.9).

Table 8.9: Estimated cellulosic ethanol yield (million litres) and the number of large biorefineries in each zone based on number of cattle, goats and sheep in Nigeria.

Alfalfa	Zone	Suitable land area (ha)	Area for livestock production (ha)	Area available for biofuel production (ha)	yield based on livestock area (tonnes)	Ethanol yield (Million litres)	Number of processing plants
	NC	10,680,921	7,234,665	3,446,256	19,747,048	607.08	10.82
	NE	11,483,514	8,221,748	3,261,766	16,406,684	504.39	8.99
	NW	8,008,434	4,062,785	3,945,649	19,412,593	596.80	10.64
	SE	1,636,434	1,121,863	514,571	3,396,172	104.41	1.86
	SS	4,924,080	1,316,325	3,607,755	24,965,663	767.52	13.68
	SW	5,513,625	2,490,776	3,022,849	23,547,991	723.93	12.90
Total		42,247,008		17,798,846	107,476,150	3,304	59
Elephant grass	NC	10,631,484	7,234,665	3,396,819	58,663,067	1,803.47	32.14
	NE	11,133,846	8,221,748	2,912,098	37,711,671	1,159.36	20.66
	NW	8,009,550	4,062,785	3,946,765	49,966,045	1,536.10	27.38
	SE	1,636,353	1,121,863	514,490	7,799,676	239.78	4.27
	SS	4,887,279	1,316,325	3,570,954	63,277,300	1,945.32	34.67
	SW	5,513,625	2,490,776	3,022,849	72,669,282	2,234.06	39.82
Total		41,812,137		17,363,975	290,087,040	7,115	159
Miscanthus x giganteus	NC	10,680,921	7,234,665	3,446,256	38,666,994	1,188.73	21.19
	NE	11,483,514	8,221,748	3,261,766	35,748,957	1,099.02	19.59
	NW	8,009,550	4,062,785	3,946,765	35,007,806	1,076.24	19.18
	SE	1,636,434	1,121,863	514,571	6,972,443	214.35	3.82
	SS	4,924,080	1,316,325	3,607,755	45,277,322	1,391.95	24.81
	SW	5,513,625	2,490,776	3,022,849	42,440,795	1,304.75	23.26
Total		42,248,124		17,799,962	204,114,317	6,275	112
Switchgrass	NC	10,680,930	7,234,665	3,446,265	28,500,613	876.19	15.62
	NE	11,483,514	8,221,748	3,261,766	23,452,098	720.98	12.85
	NW	8,155,404	4,062,785	4,092,619	28,239,071	868.15	15.47
	SE	1,636,500	1,121,863	514,637	6,062,429	186.38	3.32
	SS	4,924,080	1,316,325	3,607,755	35,175,609	1,081.40	19.27
	SW	5,513,643	2,490,776	3,022,867	43,257,222	1,329.85	23.70
Total		**42,394,071**		**17,945,909.15**	**164,687,043**	**5,063**	**90**
Multiple biomass		168,701,340		70,908,692.61	766,364,550	21,757	420

8.11 Evaluating the potential of cellulosic bioethanol and the number of processing facilities based on livestock population by state in the Northern region.

For alfalfa, Borno state has the highest suitable area for biofuel production requiring 8 processing facilities to convert 14.8 million tonnes of biomass to 454 million litres of ethanol (Table 8.7 and 8.10). Taraba state has the second highest potential in the North, with 399 million litres from 7 processing facilities. Gombe state was identified with the lowest potential at 4 million litres, where the estimated 127.4 thousand tonnes of biomass was deemed insufficient to power a large scale processing facility. Hence, recommendation would only be for a medium scale facility, if the state wishes to invest in biofuel production (Table 8.10).

For elephant grass, Borno state again has high potential for ethanol production with 39 billion tonnes of biomass requiring 21 processing facilities to produce 1.2 billion litres of cellulosic ethanol per annum. Taraba state was also identified as the second highest potential state for biofuel production in the North of Nigeria. The state was identified to require 19 processing facilities to convert 35 tonnes of elephant grass biomass to 1.1 billion litres of ethanol (Table 8.10).

Though Gombe state recorded 298 thousand tonnes of biomass with the potential to produce 9 million litres of ethanol the amount of elephant grass biomass in the state does not guarantee consistent feedstock supply to power a large scale processing facility (table 8.10), hence the recommendation for a medium scale processing facility, if the state would wish to invest in biofuel production.

For *Miscanthus x giganteus*, Borno and Taraba state were also identified as having the highest potential in the region. Like in elephant grass evaluation, Borno state will require at least 21 processing facilities to be able to convert 38 million tonnes of biomass to about 1.2 billion litres of ethanol per annum. Taraba state also had a very significant potential with 614 million litres of ethanol from 16 processing facilities, while Yobe and Bauchi states recorded 400 and 413 million litres of cellulosic ethanol per annum with 11 and 8 processing facilities respectively (Table 8.10). The North has high potential for C4 species, with elephant grass and *Miscanthus x giganteus* being the most productive crops in the region (Table 8.10).

Table 8.10: Estimated cellulosic ethanol (million litres) and number of large biorefineries in each state of the North based on livestock numbers

Species	State	Suitable land area (ha)	Area for livestock (ha)	Area for biofuel (ha)	Production (tonnes)	Ethanol production (Million litres)	Number of processing facilities
Alfalfa	Adamawa	956997	458297	498700	1895058	58	1.0
	Taraba	2720300	224182	2496118	12979814	399	7.1
	Yobe	2133432	445645	1687787	9789165	301	5.4
	Gombe	291150	250064	41086	127368	4	0.1
	Bauchi	1702827	142052	1560775	7179566	221	3.9
	Borno	3336084	698035	2638049	14773074	454	8.1
Elephant grass	Adamawa	883683	458297	425386	4551626	140	2.5
	Taraba	2471490	224182	2247308	34833275	1071	19.1
	Yobe	2133369	445645	1687724	22109184	680	12.1
	Gombe	282771	250064	32707	297637	9	0.2
	Bauchi	1688634	142052	1546582	18249670	561	10.0
	Borno	3331197	698035	2633162	38707482	1190	21.2
Miscanthus giganteus	Adamawa	956997	458297	498700	4238946	130	2.3
	Taraba	2720322	224182	2496140	29454453	906	16.1
	Yobe	2133432	445645	1687787	20422223	628	11.2
	Gombe	291150	250064	41086	246518	8	0.1
	Bauchi	1702827	142052	1560775	14983442	461	8.2
	Borno	3336084	698035	2638049	37987906	1168	20.8
Switchgrass	Adamawa	956997	458297	498700	3740247	115	2.0
	Taraba	2720322	224182	2496140	19969121	614	10.9
	Yobe	2133432	445645	1687787	12995960	400	7.1
	Gombe	291150	250064	41086	160237	5	0.1
	Bauchi	1702827	142052	1560775	13422667	413	7.4
	Borno	3336084	698035	2638049	28227124	868	15.5

8.12 Evaluating the potential of cellulosic bioethanol and the number of processing facilities based on livestock population by states in the Southern region.

In evaluating the potential of alfalfa for cellulosic ethanol production in the South of Nigeria, Oyo state has the highest potential with 9.5 million tonnes of biomass requiring 5 processing facilities to produce 293 million litres of ethanol per annum. Ogun and Ondo states were the second highest, with both having the amount of feedstock to support 5 facilities each (Table 8.11). Ogum and Ondo states recorded 279 and 276 litres of cellulosic ethanol respectively, while Lagos state has the least potential at 29 million litres of ethanol per annum (Table 8.11). Ogun and Ondo states have the potential to produce 9.1 and 9.6 million tonnes of biomass to each feed 5 processing facilities (Table 8.11).

For elephant grass, Oyo state again has the highest potential with 29 million tonnes of biomass to feed 16 facilities and produce 714 million litres of ethanol per annum (Table 8.11). Ondo and Ogun states again recorded significant ethanol production potential with 679 and 708 million litres of cellulosic bioethanol per annum respectively. The states were identified to each require 15 processing facilities to convert the feedstock. Lagos state has the lowest potential for biofuels in the region, with the potential for 2.8 million tonnes of elephant grass biomass to feed 2 processing facilities and produce 70.5 million litres of ethanol per annum (Table 8.11).

For *Miscanthus x giganteus* in the South, Ogun state recorded the highest potential with 412 million litres requiring 9 processing facilities. Oyo and Ondo states were second highest with 395 and 389 million litres while Lagos has the least potential with only 38 million litres. Oyo and Ondo states were also identified to require 9 processing facilities each to convert the available biomass while Lagos state has no capacity for a large scale facility due to inadequate biomass feedstock production potential (Table 8.11).

For switchgrass, Ogun state has the potential to feed 11 processing facilities by using 19.3 million tonnes of biomass to produce 393.4 million litres of ethanol. Oyo state has the potential to convert 19.1 million tonnes of switchgrass to 389 million litres of cellulosic ethanol per annum using 10 facilities.

Though, the SW zone has high potential for the C4 species, the study identified elephant grass as the most productive species for cellulosic ethanol production in the region (Table 8.11).

Table 8.11: Estimated cellulosic ethanol yield (million litres) and large biorefineries in each state of the Southern Nigeria based on livestock numbers.

Species	State	Suitable (ha)	Area required for livestock (ha)	Area available for biofuel (ha)	Production (tonnes)	Ethanol production (Million litres)	Number of processing plants
Alfalfa	Ekiti	439002	93647	345355	2762840	84.94	1.51
	Ogun	1238445	102630	1135815	9086523	279.35	4.98
	Ondo	1222722	216017	1006705	9060342	278.54	4.96
	Osun	771687	369832	401855	2411129	74.12	1.32
	Oyo	1683783	321642	1362141	9534989	293.13	5.22
	Lagos	157815	969	156846	941077.9	28.93	0.52
Elephant grass	Ekiti	439000	93647	345353	8979179	224.16	4.92
	Ogun	1238500	102630	1135870	28396761	708.92	15.56
	Ondo	1222722	216017	1006705	27181025	678.57	14.89
	Osun	771700	369832	401868	10448562	260.84	5.73
	Oyo	1683800	321642	1362158	28605324	714.12	15.67
	Lagos	157800	969	156831	2822964	70.47	1.55
Miscanthus x giganteus	Ekiti	439000	93647	345353	5525648	133.58	3.03
	Ogun	1238500	102630	1135870	17038056	411.89	9.34
	Ondo	1222700	216017	1006683	16106922	389.38	8.83
	Osun	771600	369832	401768	6428285	155.40	3.52
	Oyo	1684000	321642	1362358	16348299	395.21	8.96
	Lagos	157700	969	156731	1567313	37.89	0.86
Switchgrass	Ekiti	439002	93647	345355	5871035	119.60	3.22
	Ogun	1238445	102630	1135815	19308862	393.36	10.58
	Ondo	1222740	216017	1006723	18121007	369.16	9.93
	Osun	771687	369832	401855	7233386	147.36	3.96
	Oyo	1683783	321642	1362141	19069978	388.49	10.45
	Lagos	157815	969	156846	1725309	35.15	0.95

8.13 Evaluating the potential of each bioenergy crop in Nigeria based on the country's current livestock population

In evaluating the potential of single feedstocks, alfalfa has the least potential with 2.1 billion litres of cellulosic ethanol per annum, requiring 48 processing facilities (Table 8.9). This study identified elephant grass with the highest potential at 7.4 billion litres of ethanol, requiring 132 processing facilities (Table 8.9) to convert the abundant biomass. *Miscanthus x giganteus* has the second highest potential for cellulosic ethanol production with 5.2 billion litres per annum from 93 processing facilities (Table 8.9).

Switchgrass was also identified as another promising species for bioethanol production in Nigeria. The crop accounted for 4.2 billion litres of cellulosic ethanol per annum and 75 processing facilities (Table 8.9).

However, in considering the current livestock population and area required for biofuel production in Nigeria. The estimated area for livestock was subtracted from the suitable land area (grassland and shrubland). The estimation of livestock area was based on the stocking densities of the animals per hectare (Appendix 51-53; Table 8.8). About 42% (71 million ha) of the country's total grassland and shrubland (168 million ha) was realised as the free area for biofuel production, which was finally utilized to allow a sustainable production of bioethanol in Nigeria.

Therefore on multiple feedstock basis, it was found that the 41% area for biofuel production in Nigeria would potentially produce 20 billion litres of cellulosic bioethanol per annum, which far much exceeded the 10% blending target by the Federal Government of Nigeria (Table 8.9).

Chapter 9: General Discussion

9.1 An overview of the main findings

Nigeria has abundant oil reserves but with major problems/issues around its refineries as it refines only about 22% of the PMS (gasoline) that is consumed annually in the country. The country spends a significant amount of its income on the importation of refined petroleum products to meet the increasing demand. For example, in 2016, Nigeria spent an average US$21 million every day for importing fuel (using an average import exchange rate of N255 to US$1)[4]. Moreover, 50% of its total GHG emission comes from road transport following an increasing consumption of PMS over recent years. In 2015, Nigeria consumed about 18 billion litres of PMS. Hence, biofuels offer clear potential to reduce: a) the country's dependence on imported refined petroleum products; b) GHG emissions from road transport; and c) support for agricultural and rural development. The agricultural sector could make a profound contribution to the country's economic growth if its diversified and integrated with the energy sector (Nwaobi, 2005). The agricultural sector currently employs two-thirds of the nation's work force, which would have significant positive effect not only to the rural economy but also to national economic development (Ogen, 2007; Izuchukwu, 2011).

The Nigerian government introduced the country's Biofuel Policy and Incentives in 2007 (Ohimain, 2013) with the aims to reduce the nation's dependence on imported gasoline, reduce environmental pollution while at the same time creating a commercially viable industry that can support sustainable domestic jobs. To achieve these, the Nigerian National Petroleum Corporation (NNPC) was mandated to blend gasoline and diesel with 10% bioethanol and 20% biodiesel known as the E10 and B20 blends.

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[4] https://www.pressreader.com/nigeria/sunday-trust/20170129/282578787764435, last accessed 15 September 2017

A 10% blend ratio with fuel ethanol was indicated to require 1.3 billion litres of bioethanol with an estimated increase to about 2 billion litres by 2020. The Biofuel Policy also aspired to achieve 100% domestic production of biofuels consumed in the country by 2020.

Most commercial bioethanol production occurs from first generation feedstocks, i.e. sugar cane in Brazil, maize in the US and wheat in Europe. Many of the Nigerian biofuel projects have been designed to use cassava which is the country's major staple food. However, the use of first generation feedstocks in Nigeria would cause major issues with respect to food security at a time when the population of the country is increasing. A number of commercial opportunities for bioethanol production have been developed (as shown in Chapter 2, Table 2.2), however, production is still very limited. First generation ethanol production was reported to be only 134 million litres (in 2010) from five commercial ethanol distilleries mostly processing crude ethanol imported from Brazil (Ohimain, 2010). The sustainability of first generation biofuels has also been criticised especially in recent years over competition with food crops (IEA, 2010), hence, there is an urgent need to develop a more sustainable feedstock that would not compete with food. To meet the 10% replacement as mandated in the Nigerian Biofuels Policy was suggested to require about 1 million hectares of the 34 million currently under cultivation (Ohimain, 2010). With problems arising from the use of food crops and agricultural land, (Iye and Bilsborrow, 2013a, 2013b) evaluated the potential of agricultural residues for bioethanol production. The study looked at both field and processing residues from the major agricultural crops grown in Nigeria and estimated a production potential of 7.6 billion litres per annum which amounted to 28% of the projected PMS consumption by 2020 of 26 billion litres. This level also far exceeds the 10% blending requirement of the Nigerian Biofuels Policy.

The successful establishment of biofuels using available grassland and shrubland in Nigeria for the production of feedstocks for cellulosic ethanol production would clearly address some of the problems/limitations with the use of first generation feedstocks. The aim of this study was therefore to evaluate the potential of using second generation feedstocks such as alfalfa, switchgrass, *Miscanthus x giganteus* and elephant grass to produce cellulosic ethanol across the geo-political zones and states of Nigeria.

Initially it had been the intention to use government figures for land classification in Nigeria by region and by state. However, this was not possible because of the lack of availability and unwillingness of various government departments to provide access to the data without the payment of significant sums of money. Therefore it was decided to use a GIS-based approach to look at land classification using the ArcGIS AAEA (Africa Albers Equal Area Conic) projection system. From this 46 land classes were identified which were aggregated and reclassified to produce seven major classes of land use, i.e. bare area, built-up area, cropland, forest, grassland, shrubland and water bodies. Of these the built-up areas, cropland and water bodies were not used. The water bodies were excluded since the struggle for portable water is a major problem in Nigeria. Based on this several water management corporations and policies have been put in place across the regions to manage and monitor the resources (Chukwu, 2015). Forest land does have potential in the conversion of wood into bioethanol but was not considered in this study since there is already a strong policy by Federal Government of Nigeria for reforestation (EC/FAO-2003) to halt rapidly declining forest levels. The policy encourages afforestation to enable the fight against climate change through carbon sequestration (National Forest Policy, 2006). The bare land areas were initially looked at but later removed from the analysis due to the very low levels of land available in this category in addition to which there would be potentially competing uses for urban expansion to meet the needs of the growing population.

The Nigerian urban area is growing very fast, for example between 1986 and 2001 this expanded by 11% and between 2001 and 2014 by another 17% (Abimbola, 2008). This could cause serious infringement to the green areas and the agricultural land, if stringent measures are not taken to avoid the possible conflict that may arise with the biofuel industries in future (Mahmoud *et al.,* 2016).

Grassland and shrubland areas were, therefore, chosen for evaluating the potential for growing herbaceous energy crops for biofuel development in this study. Shrubland is mainly used for rough grazing of livestock (Aregheore, 2009). Nigeria's major livestock constitutes mainly of cattle, sheep and goats with a total of 13.9, 22.1 and 34.5 million animals, respectively. About 90% of the country's cattle and 70% of the goats and sheep are concentrated in the Northern part of the country (Lawal-Adebowale, 2012). Northern Nigeria was found to have more potential grassland and shrubland than the South. On a zonal basis, the North East (NE) zone was found to have the highest potential areas of shrubland and grassland at 35% and 21% of the total country areas, respectively. In the Southern Nigeria, the South West (SW) zone was found to possess the highest area of grassland and shrubland (26% and 13%) available for biofuel production. Therefore, according to this study, Nigeria's grassland is presently underutilized, with about 41% of the area not being used for livestock production and identified to be free for bioenergy crop.

For cellulosic ethanol production there is a need for crop species with high biomass production and low levels of lignin where particular focus has been on species like switch grass in the US and *Miscanthus x giganteus* in parts of Europe. To this end both of these crops in addition to elephant grass and alfalfa were evaluated for their suitability in this study.

Nigeria has a climate that is conducive to high crop and biomass production with adequate temperatures and levels of precipitation to support high rates of crop growth. Average minimum and maximum temperature varies 24ºC-32.49ºC with annual rainfall varying between 1614 and 2136 mm (Ogbuene, 2010). The four crop species evaluated in this study were used because they comprise both C3 and C4 species with their different responses to a range of climatic factors and also a range of indigenous and non-native species. The study, therefore, examined the climatic suitability for growing the four purposely grown herbaceous energy crop species in Nigeria. In addition to temperature and rainfall other factors were also evaluated for their potential effects on production, i.e. slope, elevation pH and soil OM levels. Soil is a major factor for plant growth (Baniya, 2008) since it provides the necessary medium to support growth and is an essential property for land suitability evaluations (Ayehu and Besufekad, 2015). It was also observed that slope and elevations at areas < 5%-12% and 500 meters, that are most appropriate for the selected C3 and C4 species (Orloff, 2007). This was based on the fact that the decrease in soil thickness would decrease soil fertility. Steep slope were not accepted since it can have negative influence on agricultural production.

Suitability analysis was then carried out using AHP (the Analytic Hierarchy Process) which is based on pair-wise MCDM comparisons (Saaty, 2008). In this analysis literature based information was used to classify the suitability of the different crop species in terms of: Highly suitable, Moderately suitable, Marginally suitable and Not suitable to the different geo-political zones and states of Nigeria. From this, the production potential was derived using figures from the literature for biomass conversion to ethanol. This analysis was initially carried out based on 100% utilization of the suitable land (grassland and shrubland) but later modified to include representation for the current numbers of livestock registered across the country.

Of all the four species evaluated, elephant grass was fond to have the highest potential for bioethanol production while the C3 species alfalfa had the lowest potential. The NE zone had the highest potential for bioethanol production with estimated from alfalfa, switchgrass and *Miscanthus x giganteus* of 42.3, 48 and 73 billion litres respectively, while elephant grass had the highest potential at 81 billion litres of cellulosic ethanol per annum. The study showed that the North Central zone has the second most potential with some 40 billion litres of alfalfa bioethanol. Elephant grass was exceptionally high, with the potential for 89 billion litres of cellulosic bioethanol per annum. *Miscanthus x giganteus* is the second highest species in this zone with 61 billion litres of ethanol and switchgrass the third most interesting species with 38 billion litres of cellulosic bioethanol. The North West zone produces 24 billion litres of ethanol from switchgrass but elephant grass has the highest potential with 98 billion litres of ethanol. The zone also accounted for circa 32 billion and 45 billion litres of cellulosic ethanol from alfalfa and *Miscanthus x giganteus,* respectively. In the South, of Nigeria, the South West zone was identified with the highest potential of cellulosic ethanol from elephant grass at 45 billion litres, followed by *Miscanthus x giganteus* with 22 billion litres while switchgrass has the lowest potential at 12 billion litres of cellulosic ethanol per annum. The South South showed higher potential than the South East zone where elephant grass produced 33 billion litres compared to the 11 billion litres of cellulosic ethanol per annum realised from elephant grass in the SE zone.

In terms of the most productive state for bioenergy production in the North of Nigeria, Borno state had the highest potential in the North with Oyo state prevailing in the South. Borno accounted for approximately 12 billion litres of cellulosic bioethanol, with the elephant grass producing the highest level at 22 billion litres followed by *Miscanthus x giganteus* with 20 billion litres of ethanol per annum.

Gombe state had the lowest potential in the North where alfalfa produced only 1.7 billion litres of cellulosic ethanol. On the basis of the results presented Gombe state is therefore not recommended for biofuel development due to the extremely low production potential of the location for growing the feedstocks.

In terms of ethanol productivity in the South, the study showed that Oyo state has the highest potential with a total of 5.7 billion litres from alfalfa, switchgrass with 7.6 billion litres, *Miscanthus x giganteus* about 7.3 billion and elephant grass with the highest potential at 14.6 billion litres of ethanol per annum. The study further indicated that Lagos state possess the least biofuel potential in the South of Nigeria. The state recorded only about 600 million litres of cellulosic bioethanol from alfalfa biomass. Switchgrass produced about 700 million litres, *Miscanthus x giganteus* with 800 million litres of ethanol, while elephant grass 1.5 billion litres of cellulosic bioethanol per annum.

Based on 100% utilization of the study area for cellulosic ethanol production, Nigeria has the potential for 338 and 236 billion litres per annum from elephant grass and *Miscanthus x giganteus* respectively, while alfalfa with the least potential can deliver about 155 billion litres per annum. It is interesting to note that on a multiple feedstock basis, Nigeria stands the chance of producing 876 billion litres of cellulosic ethanol annually to meet her domestic energy demand and still have in excess biofuels available for export. But the possible problem that would arise from the 100% utilization of the national grazing land would be a case of feed versus fuel conflict and displacing current livestock activities.

The use of 100% of available grassland and shrubland in Nigeria is not possible due to the significant impacts that this would have on livestock production. Therefore the scenario was investigated which looked at the current livestock population in Nigeria and therefore arrived at 41% free land for biofuel production after the deduction of the livestock areas.

The results showed that the North has significantly higher livestock population compared to the South, where the NW zone alone accounted for over 50% of the country's total livestock population. Based on the large scale production of livestock in the NW, it was found that the zone would require more grazing land for its increasing livestock, but still have free land available for biofuel production.

Against the background of the livestock population in Nigeria, the 42% free land deduced for biofuel feedstock production showed that the NC zone has the highest potential for cellulosic ethanol from alfalfa with 607 million litres with the potential to feed 11 large scale processing facilities, the NW 597 litres of ethanol and 11 large processing facilities, while the NE zone with 504 litres of cellulosic ethanol and 9 processing facilities. The SS zone in the South of Nigeria, surpassed the SW zone with 767 million litres of cellulosic ethanol and 14 processing facilities, to be rated the highest zone with the potential for cellulosic bioethanol production. The significant ethanol yield in the SS zone was due to the fact that the SW zone has over half of the total livestock population in the Southern region and would require more land. The SE zone has the lowest potential in the regions with 104 million litres and 2 processing facilities from alfalfa.

The SW zone accounted the highest potential with 2.2 billion litres from elephant grass and 40 large scale processing facilities, the SS zone is second with 2.0 billion litres of cellulosic ethanol and 35 large scale facilities while the SE zone has the lowest potential with 240 million litres of cellulosic ethanol and 2 large processing facilities. The NC zone had the highest potential for 1.8 billion litres of ethanol from elephant grass and 32 large scale processing facilities, the NW with a potential for 1.5 billion litres of cellulosic ethanol and 27 large processing facilities while the NE zone has the potential for 1.2 billion litres of cellulosic ethanol per annum and 21 large scale facilities.

In terms of the potential of *Miscanthus x giganteus* for cellulosic ethanol production, the SS zone has the highest potential with 1.4 billion litres per annum and 25 large processing facilities compared to the SW zone which accounted the highest potential for ethanol production from elephant grass and switchgrass. The SW accounted for 2.2 and 1.4 billion litres of cellulosic ethanol from the species per annum to power 40 and 24 large scale commercial facilities respectively.

In terms of the potential for the individual states in the North, Borno state had the highest potential for cellulosic ethanol from almost all the entire energy crops, particularly elephant grass and *Miscanthus x giganteus* with 1.2 billion litres and 21 large facilities for each of the species. Gombe state has the lowest potential for almost all the species, though recorded 8 and 9 million litres of ethanol per annum for both *Miscanthus x giganteus* and switchgrass, but the biomass would not be able to power a large scale bio-refinery. Based on the insufficient resources, the state is therefore recommended for a medium scale processing facility, if this state wishes to invest in biofuel production.

In the Southern region, Oyo state has the highest potential for cellulosic ethanol production with 714 million litres ethanol from elephant grass per annum and 16 processing facilities while Ogun state accounted the highest potential for *Miscanthus x giganteus* and switchgrass with 412 million and 393 million. To allow for the ethanol conversion the resources require 9 and 11 large scale processing facilities to power it.

Lagos state, the most developed and populated state in Nigeria has as expected the least overall potential for t all the energy crops with only elephant grass recording about 70 million litres of cellulosic ethanol per annum. It was also found that the state has little or no potential for a large scale processing facility except for elephant grass with the potential to power only 1 large bio-refinery.

However, elephant grass, *Miscanthus x giganteus* and switchgrass which were identified to possess the highest potential for cellulosic ethanol are therefore recommended for policy makers as the best feedstocks while alfalfa with the lowest potential is not recommended for cellulosic bioethanol production in Nigeria.

The multiple feedstock comparison is particularly important since many countries are currently looking forward to use it for cellulosic bioethanol production.

According to this estimation, the Southern region has been identified to possess higher potential compared with the North, where the SW zone accounted for the overall highest potential across the country with 5.6 billion litres and 100 processing facilities (Table 9.1 - 9.2). Also, the SS zone has the second highest potential with 5.2 billion litres and 92 large scale facilities while the SE zone had the lowest potential for ethanol production across the country with only 745 million litres and 13 processing facilities (Table 9.1). The NC zone had the highest across the Northern region, though could be rated as the third largest potential in the country with 4.5 billion litres and 80 processing facilities. The NE is the second most potential zone with 3.5 billion litres per annum and 62 processing facilities (Table 9.2).

Table 9.1: Estimated cellulosic ethanol yield (million litres) and large bio-refinery in each zone based on multiple feedstock use in Southern Nigeria taking into consideration areas required for livestock production.

SE				SS			SW		
Feedstock	Biomass prod^n (tonnes)	Ethanol yield	No of processing facilities	Biomass prod^n (tonnes)	Ethanol yield	No of processing facilities	Biomass prod^n (tonnes)	Ethanol yield	No of processing facilities
Alfalfa	3,396,172	104	2	24,965,663	768	14	23,547,991	724	13
Elephant grass	7,799,676	240	4	63,277,300	1,945	35	72,669,282	2,234	40
Miscanthus x giganteus	6,972,443	214	4	45,277,322	1,392	25	42,44,0795	1,305	23
Switchgrass	6,062,429	186	3	35,175,609	1,081	19	43,257,222	1,330	24
Multiple	24,230,720	745	13	168,695,893	5,186	92	181,915,291	5,593	100

Table 9.2: Estimated cellulosic ethanol yield (million litres) and large bio-refinery by zone based on multiple feedstock use in Northern Nigeria taking into account land area used for livestock production.

NC				NE			NW		
Feedstock	Biomass prod[n] (tonnes)	Ethanol yield	Plants	Biomass prod[n] (tonnes)	Ethanol yield	No of processing facilities	Biomass prod (tonnes)	Ethanol yield	No of processing facilities
Alfalfa	19,747,048	607	11	16,406,684	504	9	19,412,593	590	10
Elephant grass	58,663,067	1803	32	37,711,671	1159	21	49,966,045	1,536	27
Miscanthus x giganteus	38,666,994	1189	21	35,748,957	1099	20	35,007,806	1,076	19
Switchgrass	28,500,613	876	16	23,452,098	721	13	28,239,071	868	15
Multiple	145,577,721	4475	80	113,319,410	3,484	62	132,625,515	4070	71

Based on the 10% blending target and considering the current (2015) PMS (NNPC, 2014, 2015) consumption at 49 million litres per day, it was indicated that the country's biofuel potential at 41% utilization of the free land for the feedstock production would account for 20 billion litres of cellulosic bioethanol per annum. This amount was far much greater than the 10% blending target by the Federal Government of Nigeria at 1.8 billion litres per annum. The 20 billion litres per annum would have the potential to totally satisfy Nigeria's PMS consumption.

Generally, transportation logistics of feedstock production and supply to the various processing facilities are one of the major barriers confronting second generation biofuel production especially when dealing with high volume low density materials. This is particularly more challenging in Nigeria where there is limited number of heavy trucks as well as the poor road network in the rural communities assessable to allow for the delivery of the feedstocks (Iye and Bilsborrow, 2013b). However, as with agricultural residues, the expectation would be delivery by farmers to central collection points to enable them to centralise the various feedstocks before it will be finally conveyed by a third party to the bio-refineries. This remains a key limitation of the potential for herbaceous energy crops to contribute towards biofuel production in Nigeria.

9.2. Major challenges and limitations of the study

The major problem was that the required statistical datasets and information for this study was not available in Nigeria. This problem was solved by using spatial datasets obtained from the FAO website.

Secondly, further problem was encountered during projections were the UTM projection systems was employed but the outcome was totally off the country's area. Based on the discrepancies, the AAEA projection system was recommended and employed to obtain more robust results.

9.3 Study's contributions to knowledge

Considering the gaps and originality, the study was able to address the fifth recommendation from Iye (2013a) by evaluating the suitability and potentials for growing selected herbaceous energy crops, such as *Miscanthus x giganteus,* switchgrass and others. Hence, the estimations from this study are particularly useful for policy planners, industry and other organisations that would wish to embark on biofuel production in Nigeria. This study also addresses the land use issues related to the Nigerian Biofuel Policy which was designated to make agricultural land available for biofuel development in Nigeria (Anyaoku, 2007; NNPC, 2007). Nonetheless, this policy did not consider the possible 'food versus fuel' competition that will arise as a result of land use change, i.e. from land used for the conventional staple food production that feeds the country to cropland for bioenergy production. The policy also failed to acknowledge the current high rate of food imports in the country (Akpan, 2009; Odularu, 2008). Hence, decision makers should reconsider their policies and tried to promote measures that will avoid the food versus fuel debate.

Subsequent studies highlighted that Nigeria has suitable climate and soil conditions for biofuel development (Dick, 2014), but they did not point out where the land exists and how can be used to increase this development. Iye and Bilsborrow (2013a) recommended evaluation of land suitability for purposely grown bioenergy crops in order to enable cultivation of these crops across the regions of Nigeria. Hence, this study addressed the following:

1. It estimated the most suitable states in Nigeria for the bioenergy crops such as alfalfa, switchgrass, *Miscanthus x giganteus* and elephant grass.
2. It also accessed the biomass productivity of these four species across the six geo-political zones and states, as well as the highest potential species among the four.
3. It estimated the theoretical ethanol yield and potential number of large and medium scale commercial process facilities (bio-refineries) required to be constructed in each state and zone to enable the best use of the available resources.
4. It provided land cover data on the national, zonal and state basis which were not appropriately identified in other studies. Moreover, most of the other studies classified the shrubland areas alongside the grassland, but this study was able to separate them. The bare land which was previously classified alongside the built-up area was also separated.

9.4 Recommendations for future work

Based on the available information from the thesis, the following areas are recommended for future work.

1. Since the ethanol productivity for each bioenergy crop was based on estimation of the theoretical yield there is need for appropriate field trials and laboratory experiments, basically by fermentation of reducing sugars to determine the actual cellulosic bioethanol yield of each bioenergy crop. This would help validate the results used in this study.
2. Since the identified land cover classes were identified from GIS the data will require "*ground truthing*" for validation.
3. Future study evaluating the suitability and potential of the bioenergy crops will require to carry out buffering during the GIS classification to ensure that bounding areas around the regions, zones and states will be noted in order to identify specified points or maximum distances within segments.
4. Future studies to develop a model that will validate the land suitability and productivity of the selected bioenergy crops based on the economic feasibility of each crop species, considering the increasing biomass yields, production costs and transportation costs from the plantation sites to the closest biorefineries. This would be a case of using information obtained from both the farmers and bioenergy industries to address issues related to the feasibility of the species, like the reduction of land area and potential competition for food, feed and fuel.

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Appendices

Appendix 1: Description of the 46 land cover classes

Label	Data description
11	Irrigated croplands: These are managed arable areas for agricultural production based on irrigation facilities.
12	Irrigated shrub or tree crops: These are woody plantation areas such as cash crops and orchards used for agricultural production irrigation method of farming system is used due to insufficient rainfall distribution.
13	Irrigated herbaceous crops: These comprises of agricultural lands provided with artificial regular water supply to irrigate crops. There are categorised into further subdivisions; surface irrigation, sprinkler irrigation and drip irrigation systems.
14	Rain-fed croplands: These include arable areas for planting crops as a result of sufficient rainfall distribution in the location.
15	Rain-fed herbaceous crops: These include land areas for planting non persistent woody stem above ground crops.
16	Rain-fed shrub or tree crops: These are permanent crop areas used for the production of woody plants such as cash crops, vineyards, olive tree and orchards
20	Mosaic cropland: These are lands with a mosaic of annual crops which comprises of (50-70%) and trees vegetation between (20-50%)
21	Mosaic cropland/grassland/shrub land: These are lands with a mosaic of crops in which neither component comprises of grassland or shrub land between (20-50%).
30	Mosaic vegetation/cropland: These are lands with a mosaic of annual crop and grassland/shrub land/forest in which neither component comprises between (20-50%) and (50-70%).
31	Mosaic grassland or shrubland: These are land areas with mosaic of grassland with a component comprising of (50-70%) and cropland (20-50%).
32	Mosaic forest/cropland: These includes mosaic land with trees and shrubs comprising 50-70% and cropland between 20-50%.
40	Closed to open broadleaved evergreen or semi-deciduous forest: These are land areas comprising of trees with more than 15% canopy and crown covers and a height greater than 5 meters long.
41	Closed broadleaved evergreen or semi-deciduous forest: These are formations where trees in various canopy cover over 40% of the ground and with the height greater that 5meters long.

Appendix 2: Description of the 46 land cover classes (continued)

42	Open broadleaved semi-deciduous and/or evergreen forest: These are land areas with a formation of cover between 15-40%, a continuous grass layer is observed here which permits grazing in the area.
50	Closed broadleaved deciduous forest: These are forests with more than 40% of tree crown covers of deciduous species.
60	Open broadleaved deciduous forest/woodland: These are forest areas without much vegetation between15-40% and 5 m length but with trees that contains outrageous amount of flowers.
70	Closed needle leaved evergreen forest: These are forest areas with more than 40% crown cover and a length greater than 5m.
90	Open needle leaved deciduous or evergreen forest: These are trees with at least 10% and less than 40% (15-40%) cover canopy.
91	Open needle leaved deciduous forest: These includes trees with a percentage crown cover between 15-40%, although with a height greater than 5m.
92	Open needle leaved evergreen forest: This is an open canopy in which at least 15% and less than 40% of the area is covered by trees.
100	Closed to open mixed broadleaved and needle leaved forest: This include forest areas with less than15% canopy coverage and with more than 5m height.
101	Closed mixed broadleaved and needle leaved forest: These are forest areas with cover canopy of greater than 40% and a greater than 5m.
110	Mosaic forest or shrubland / grassland: These includes mosaic land with trees and shrubs with a cover canopy between 50-70% and grassland comprising at least 20% but not more than 50%.
120	Mosaic grassland with a cover canopy between 50-70% and forest or shrub land comprising of 20-50%.
130	Closed to open broadleaved or needle leaved evergreen or deciduous shrubland: these are small trees of less than 5m height and a cover canopy below 15%.
131	Closed to open broadleaved or needle-leaved evergreen shrubland: These are areas occupied by small short tree of less than 5m and a coverage below 15%.
134	Closed to open broadleaved deciduous shrubland: These include land areas dominated by woody vegetation below 15% and a height exceeding 2m. However canopy here is never without green foliage
140	Closed to open herbaceous vegetation: These include areas comprising of grasses or lichens/mosses and scattered trees greater than 15% canopy covers.
141	Closed grassland: These includes land areas comprising of herbaceous trees and grasses with canopy coverage of more than 40%.
143	Open grassland: These are lands which consist of herbaceous trees and grasses with canopy covers between 10-40%. It is primarily used for pasture and grazing functions.

Appendix 3: Description of the 46 land cover classes (continued)

150	Sparse vegetation: These includes lands with exposed soils and with less than 15% vegetated cover canopy at any time of the year.
151	Sparse grassland: These includes lands with exposed soils and herbaceous trees and shrubs crown covers of less than 15%.
152	Sparse shrub land: These includes lands with woody vegetation comprising of trees and shrub less than 15% cover canopy.
160	Closed to open broadleaved forest regularly flooded (temporarily) - Fresh or brackish water: These are lands dominated by broadleaf trees with greater than 15% canopy cover and a height exceeding 2 m. This consists of tree communities with annual cycle of leaf-on and-off periods.
161	Closed to open broadleaved forest on (semi-)permanently flooded land - Fresh water: These are lands dominated by broadleaf trees with greater than 15% canopy covers and a height exceeding 2meters. Trees in these land area remains green all year round and the canopy is never without green foliage.
162	Closed to open broadleaved forest on temporarily flooded land - Fresh water: Closed to open broadleaved forest regularly flooded (temporarily) - Fresh or brackish water: These are lands dominated by broadleaf trees with greater than 15% canopy covers and a height exceeding 2 m. This consist of tree communities with annual cycle of leaf-on and-off periods.
170	Closed broadleaved forest or shrub land permanently flooded - Saline or brackish water: These are lands comprising of woody vegetation with a cover canopy between 40-60% and a height exceeding 5meters.
180	Closed to open grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water: These are lands comprising of herbaceous covers less than 10% and trees/ shrubs greater than 15% cover canopy.
181	Closed to open woody vegetation on regularly flooded or waterlogged soil - Fresh or brackish water: These comprises of lands with herbaceous greater than15% and other understory systems as well as forest cover between 30-60% and a height exceeding 2 m.
185	Closed to open (>15%) grassland on regularly flooded or waterlogged soil - Fresh or brackish water: These comprises of lands with herbaceous greater than15% and other understory systems as well as forest cover between 30-60% and a height greater than 5 m.
190	Built-up areas: These are developed areas covered by building and other man-made structure and covered with at least 60 meters wide.
200	Bare areas: These are lands with minimal ability to support vegetation, these includes areas of exposed soil, sand, gravel and rock with less than 10% cover.
201	Consolidated bare areas: These include areas characterized by solid and firm surface as well as lands with the presence of coarse fragmented surfaces which are not penetrable with the effect of traditional agricultural materials such as spade or a hoe, this land surface of these areas can also remain coherent and hard even when moist.
202	Non-consolidated bare areas: These include surface areas such as stony or sandy desert covered as a resulting of the effects of moisture and temperature as well as macro- /micro-organisms.
210	Water: All water bodies with a size that is greater than 0.08hectares.

Appendix 4: Aggregation and Reclassification of land cover classes using generalization method

Value	Label	Colour	Value 2	Aggregation1	Aggregation 2	Aggregation 3
11	Irrigated croplands (or aquatic)					
12	Irrigated shrub or tree crops					
13	Irrigated herbaceous crops		11	Irrigated cropland	Cropland	
14	Rainfed croplands					
15	Rainfed herbaceous crops					
16	Rainfed shrub or tree crops (cash crops, vineyards, olive tree and orchard)		14	Rain fed cropland	Cropland	
20	Mosaic cropland (50-70%) / vegetation (grassland/shrub land/forest) (20-50%)					
21	Mosaic cropland (50-70%) / forest (50-70%)					
22	Mosaic cropland (50-70%) / grassland or shrubland (20-50%)		20	Mosaic cropland (50-70%) /vegetation (20-50%)	Cropland	Cropland
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)					
31	Mosaic grassland or shrubland (50-70%) / cropland (20-50%)		30	Mosaic vegetation (50-70%) /cropland (20-50%)	Grassland	Grassland
32	Mosaic forest (50-70%) / cropland (20-50%)		32	Mosaic forest (50-70%) / cropland (20-50%)	Forest	Forest
40	Closed to open (>15%) broadleaved evergreen forest (>5m)		40	Closed to open (>15%) broadleaved evergreen forest (>5m)	Shrub land	Shrub land
41	Closed (>40%) broadleaved evergreen or semi deciduous forest (>5m)					
42	Open (15-40%) broadleaved evergreen or semi deciduous forest (>5m)					
50	Closed (>40%) broadleaved deciduous forest (>5m)		41	Open (15-40%) broadleaved evergreen/ semi deciduous forest (>5m)	Forest	Forest
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)					
70	Closed (>40%) needleleaved evergreen forest (>5m)					
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)		60	Closed to open (>40%) needleleaved evergreen forest (>5m)	Forest	Forest

91	Open (15-40%) needleleaved deciduous forest (>5m)					
92	Open (15-40%) needleleaved evergreen forest (>5m)					
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)					
101	Closed (>40%) mixed broadleaved and needleleaved forest (>5m)					
102	Open mixed broadleaved and needleaved forest					
110	Mosaic forest-shrubland (50-70%)/grassland (20-50%)		110	Mosaic forest-shrub land (50-70%)/grassland (20-50%)	Grassland	
120	Mosaic grassland (50-70%)/forest or Shrubland (20-50%)		120	Mosaic grassland (50-70%)/forest or Shrub land (20-50%)	Grassland	Grassland
130	Closed to open (>15%) (broadleaved/ needleleaved, evergreen/deciduous) shrubland (<5m)					
131	Closed to open (>15%) broadleaved or needle-leaved evergreen shrubland (<5m)		130	Closed to open (>15%) (broad /needleaved evergreen /deciduous) shrub(<5m)	Shrub land	
134	Closed to open (>15%) broadleaved deciduous shrubland (<5m)		134	Closed to open (>15%) broadleaved deciduous shrubland (<5m)	Shrub land	Shrub land
140	Closed to open (>15%) herbaceous vegetation (grassland, savannahs or lichens/mosses)		140	Closed to open (>15%) herbaceous vegetation (grassland, savannas)	Grassland	
141	Closed (>40%) grassland		141	Closed (>40%) grassland	Grassland	Grassland
143	Open (<15%) grassland					
145	Lichens or Mosses		143	Open (<15%) grassland	Bare land	
150	Sparse (<15%) vegetation		150			
151	Sparse (<15%) grassland					
152	Sparse (<15%) shrubland					
153	Sparse (<15%) tree			Sparse (<15%) vegetation	Bare land	

160	Closed to open (>15%) broadleaved forest regularly flooded (temporarily)-Fresh/brackish water					
161	Closed to open broadleaved forest on (semi-) permanently flooded land - Fresh water					
162	Closed to open broadleaved forest on temporarily flooded land - Fresh water		160	Closed to open (>15%)broadleaved forest - temporarily flooded	Fresh water	
170	Closed (>40%) broadleaved forest or shrubland permanently flooded - Saline or brackish water		170	Closed (>40%) broad. forest or shrubland-permanently flooded	Brackish water	Water
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded - Fresh /saline water					
181	Closed to open (>15%) woody vegetation on regularly flooded - Fresh or brackish water					
185	Closed to open (>15%) grassland on regularly flooded-Fresh or brackish water		180	Closed to open (>15%) grass/woody vegetation regularly flooded	Fresh water	Water
190	Artificial surfaces and associated areas (Urban areas >50%)		190	Artificial surfaces and associated areas (Urban areas >50%)	Built-up	Built-up
200	Bare areas		200	Bare areas	Bare area	
201	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)		201	Consolidated bare areas (hardpans, gravels, rock, stones)	Bare area	
202	Non-consolidated bare areas (sandy desert)					
203	Salt hardpans		202	Non-consolidated bare areas (sandy desert)	Bare area	Bare area
210	Water bodies		210	Water bodies	Fresh water	Water

Appendix 5: The derived areas of Nigeria LC classes by state and FCT

Abia	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
	Bare area	32786	12577458	12.6	1258	0.3
	Cropland	69547	8535219	8.54	854	0.2
	Forest	3788222	2155501909	2156	215550	46
	Grassland	2301379	869329305	869	86933	18
	Shrubland	3543250	1674254215	1674	167425	35
			4720198105	4720	472020	100
Adamawa	Bare area	128879	21252705	21.3	2125	0.1
	Built-up area	38868	23409197	23.4	2341	0.1
	Cropland	14434962	20117280503	20117	2011728	59
	Forest	9691491	3844053713	3844	384405	11
	Grassland	3609837	796099068	796	79610	2.3
	Shrubland	21571229	9160296595	9160	916030	27
	Water bodies	690189	257954488	258	25795	0.8
			34220346271	34220	3422035	100
Akwa Ibom	Bare area	101592	11957240	11.96	1196	0.2
	Cropland	198333	39178993	39.2	3918	0.6
	Forest	5613439	3098648563	3099	309865	46
	Grassland	2567731	906931703	907	90693	13
	Shrubland	4998142	2540954218	2541	254095	38
	Water bodies	493644	126491677	126	12649	1.9
			6724162394	6724	672416	100

Appendix 6: The derived areas of Nigeria LC classes by state and FCT (continued)

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Anambra	Bare area	166254	34907740	34.9	3491	0.8
	Built-up area	21155	12224463	12.2	1222	0.3
	Cropland	48603	6281169	6.28	628	0.1
	Forest	4220043	2235838163	2236	223584	49
	Grassland	3323380	1479354034	1479	147935	32
	Shrubland	2311248	716438059	716	71644	16
	Water bodies	410154	101420840	101	10142	2.2
			4586464468	4586	458646	100
Bauchi	Bare area	4535941	1752288540	1752	175229	3.6
	Built-up area	37057	31358796	31.36	3136	0.1
	Cropland	22834723	29244737177	29245	2924474	60
	Forest	3291279	1006101719	1006	100610	2.1
	Grassland	19472995	10582197616	10582	1058220	22
	Shrubland	12625929	6386732433	6387	638673	13
	Water bodies	237231	49101960	49.1	4910	0.1
			49052518240	49053	4905252	100
Bayelsa	Forest	5270779	1350145801	1350	135015	14
	Grassland	9445794	3555102123	3555	355510	37
	Shrubland	9834830	2710957452	2711	271096	28
	Water bodies	7319574	2106117053	2106	210612	22
			9722322429	9722	972232	100

Appendix 7: The derived areas of Nigeria LC classes by state and FCT (continued)

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Benue	Bare area	137904	18366944	18.37	1837	0.1
	Cropland	7374546	3938447191	3938	393845	13
	Forest	18926743	11162253712	11162	1116225	36
	Grassland	3404404	941695657	942	94170	3.0
	Shrubland	25029780	15029653739	15030	1502965	48
	Water bodies	823950	228421152	228	22842	0.7
			31318838396	31319	3131884	100
Borno	Bare area	10356341	4397784563	4398	439778	6.7
	Built-up area	55495	28974631	29.0	2897	0.0
	Cropland	38088553	27386863897	27387	2738686	41
	Forest	1459023	325545323	326	32555	0.5
	Grassland	46407903	27038350105	27038	2703835	41
	Shrubland	21793991	6781969528	6782	678197	10
	Water bodies	205121	152294941	152	15229	0.2
			66111782987	66112	6611178	100
Cross River	Bare area	101161	16683529	16.7	1668	0.1
	Cropland	401124	62770671	62.8	6277	0.3
	Forest	15589189	10796081425	10796	1079608	51
	Grassland	6353628	2640686385	2641	264069	12
	Shrubland	13781784	7241470423	7241	724147	34
	Water bodies	1655763	405891749	406	40589	1.9
			21163584181	21164	2116358	100
Delta	Bare area	77091	9640624	9.6	964	0.1
	Cropland	41956	6485150	6.5	649	0.0
	Forest	12054731	3338803612	3339	333880	20
	Grassland	14036804	4923429139	4923	492343	30
	Shrubland	18908817	5712019316	5712	571202	34
	Water bodies	10327230	2610594488	2611	261059	16
			16600972329	16601	1660097	100

Appendix 8: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Ebonyi	Bare area	15716	1902795	1.9	190	0.0
	Cropland	982773	301329090	301	30133	4.9
	Forest	3654356	1523216088	1523	152322	25
	Grassland	1760625	675752138	676	67575	11
	Shrubland	4595999	3682911780	3683	368291	60
	Water bodies	8920	1261445	1.3	126	0.02
			6186373335	6186	618637	100
Edo	Bare area	28272	3380895	3.4	338	0.0
	Built-up area	35564	52952054	53	5295	0.3
	Cropland	411793	78009029	78	7801	0.4
	Forest	11434206	3933229485	3933	393323	20
	Grassland	14648613	6365970685	6366	636597	33
	Shrubland	20093735	8953563190	8954	895356	46
	Water bodies	891820	199809338	200	19981	1.0
			19586914675	19587	1958691	100
Ekiti	Bare area	5113	748297	0.75	74.8	0.0
	Cropland	428919	80837291	81	8084	1.5
	Forest	1679937	737650166	738	73765	14
	Grassland	3205934	2157525843	2158	215753	41
	Shrubland	4689144	2248194461	2248	224819	43
	Water bodies	34536	9321363	9.32	932	0.2
			5234277421	5234	523428	100

Appendix 9: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Enugu	Bare area	81787	20208260	20.2	2021	0.3
	Built-up area	40479	52488806	52.5	5249	0.7
	Cropland	356140	57545984	57.5	5755	0.7
	Forest	7133175	3333173945	3333	333317	43
	Grassland	3499983	1742715966	1743	174272	23
	Shrubland	5154654	2491363868	2491	249136	32
	Water bodies	2175	231636	0.23	23.2	0.0
			7697728466	7698	769773	100
FCT	Bare area	12845	1411930	1.41	141	0.0
	Built-up area	78094	162881026	163	16288	2.2
	Cropland	3099179	1512576344	1513	151258	21
	Forest	3367237	1097396104	1097	109740	15
	Grassland	505197	100582986	101	10058	1.4
	Shrubland	6503088	4465432702	4465	446543	61
	Water bodies	26100	10385335	10	1039	0.1
			7350666427	7351	735067	100
Gombe	Bare area	476698	81039006	81	8104	0.4
	Built-up area	37664	18058240	18	1806	0.1
	Cropland	7896086	14989176022	14989	1498918	82
	Forest	494765	82985819	83	8299	0.5
	Grassland	5365480	1744296097	1744	174430	10
	Shrubland	2924664	1101868321	1102	110187	6.1
	Water bodies	241037	171227670	171	17123	0.9
			18188651175	18189	1818865	100

Appendix 10: The derived areas of Nigeria LC classes by state and FCT (continued).

Imo	Bare area	9204	2583477	2.6	258	0.0
	Cropland	9390	977353	1.0	98	0.0
	Forest	5032178	2101040044	2101	210104	40
	Grassland	2953381	1673347119	1673	167335	32
	Shrubland	4210655	1381335855	1381	138134	26
	Water bodies	778841	150552890	151	15055	2.8
			5309836738	5310	530984	100
Jigawa	Bare area	10525684	8177968320	8178	817797	34
	Built-up area	27481	7106189	7.11	711	0.03
	Cropland	8022857	5084514515	5085	508451	21
	Forest	11556	1757281	1.76	176	0.01
	Grassland	18040262	10552997048	10553	1055300	44
	Shrubland	572536	140392942	140	14039	0.6
	Water bodies	137892	28575674	29	2858	0.1
			23993311968	23993	2399331	100
Kaduna	Bare area	145138	19435402	19	1944	0.04
	Built-up area	156321	264794747	265	26479	0.6
	Cropland	18072455	24833381188	24833	2483338	56
	Forest	11946417	4630495178	4630	463050	10
	Grassland	4170870	784085101	784	78409	2
	Shrubland	26043108	13705317182	13705	1370532	31
	Water bodies	183046	72916335	73	7292	0.2
			44310425133	44310	4431043	100

Appendix 11: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Kano	Bare area	1649754	576476664	576	57648	2.9
	Built-up area	234901	122282887	122	12228	0.6
	Cropland	10375151	12375211619	12375	1237521	62
	Forest	220568	56143185	56	5614	0.3
	Grassland	10744032	6053318262	6053	605332	30
	Shrubland	1073338	608682509	609	60868	3.0
	Water bodies	419399	285551478	286	28555	1.4
			20077666605	20078	2007767	100
Katsina	Bare area	7206517	4442758670	4443	444276	19
	Built-up area	62370	20974399	21.0	2097	0.1
	Cropland	7415279	5685058768	5685	568506	24
	Grassland	14224309	13453553594	13454	1345355	57
	Shrubland	114284	21402289	21.4	2140	0.1
	Water bodies	219668	77740506	77.7	7774	0.3
			23701488226	23701	2370149	100
Kebbi	Bare area	3600063	1185929645	1186	118593	3.3
	Built-up area	14159	9818042	10	982	0.0
	Cropland	16363973	24464149462	24464	2446415	68
	Forest	384929	72974964	73	7297	0.2
	Grassland	14213807	7460092390	7460	746009	21
	Shrubland	4857510	1917819997	1918	191782	5.4
	Water bodies	709611	726018828	726	72602	2.0
			35836803328	35837	3583680	100

Appendix 12: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Kogi	Bare area	363962	52698165	52.7	5270	0.2
	Built-up area	35553	34756480	34.8	3476	0.1
	Cropland	2352848	591657128	592	59166	2.0
	Forest	20989223	14519217998	14519	1451922	50
	Grassland	5360236	1722311979	1722	172231	6.0
	Shrubland	21420755	11649541387	11650	1164954	40
	Water bodies	862273	366252765	366	36625	1.3
			28936435903	28936	2893644	100
Kwara	Bare area	77280	11345901	11.3	1135	0.0
	Built-up area	37289	60157884	60.2	6016	0.2
	Cropland	4550548	1465910833	1466	146591	4.1
	Forest	23018890	15864806236	15865	1586481	45
	Grassland	4465991	1087154504	1087	108715	3.1
	Shrubland	25076989	16836113310	16836	1683611	48
	Water bodies	258835	86780491	87	8678	0.2
			35412269158	35412	3541227	100
Lagos	Built-up area	274512	600775477	601	60078	16
	Cropland	3971	900000	0.9	90	0.02
	Forest	1663992	411985470	412	41199	11
	Grassland	2584180	1096187016	1096	109619	29
	Shrubland	2832997	778696342	779	77870	21
	Water bodies	1246176	894666533	895	89467	24
			3783210838	3783	378321	100

Appendix 13: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Nasarawa	Bare area	162702	19721554	19.72	1972	0.1
	Built-up area	13610	7598195	7.60	760	0.03
	Cropland	10335344	5761437864	5761	576144	22
	Forest	9621151	3496605603	3497	349661	13
	Grassland	1589603	299627623	300	29963	1.1
	Shrubland	20410035	16463510028	16464	1646351	63
	Water bodies	618497	273314984	273	27331	1.0
			26321815851	26322	2632182	100
Niger	Bare area	953481	138105887	138	13811	0.2
	Built-up area	52844	40985178	41	4099	0.1
	Cropland	33015377	29511480369	29511	2951148	42
	Forest	21740898	9933722836	9934	993372	14
	Grassland	5462154	1384083174	1384	138408	1.9
	Shrubland	53750080	28555343900	28555	2855534	40
	Water bodies	2251193	1440918558	1441	144092	2.0
			71004639902	71005	7100464	100
Ogun	Bare area	728440	257517634	258	25752	1.6
	Built-up area	110128	106120705	106	10612	0.7
	Cropland	1511757	577403157	577	57740	3.6
	Forest	5736844	2289112568	2289	228911	14
	Grassland	11369539	7385429261	7385	738543	46
	Shrubland	12092722	5254805238	5255	525481	33
	Water bodies	977660	212554911	213	21255	1.3
			16082943473	16083	1608294	100

Appendix 14: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Ondo	Built-up area	27000	31500000	31.5	3150	0.2
	Cropland	329468	57843935	57.8	5784	0.4
	Forest	6538757	1753004188	1753.0	175300	12
	Grassland	11725734	6444930388	6444.9	644493	44
	Shrubland	14515310	6020248696	6020.2	602025	42
	Water bodies	828523	189927870	189.9	18993	1.3
			14497455077	14497.5	1449746	100
Osun	Bare area	21441	3547991	3.55	355	0.04
	Built-up area	12798	9914062	9.91	991	0.1
	Cropland	864369	181983825	181.98	18198	2.0
	Forest	3970502	1161425597	1161.43	116143	13
	Grassland	7022092	3962888279	3962.89	396289	43
	Shrubland	9453726	3790161835	3790.16	379016	41
	Water bodies	351120	76988330	76.99	7699	0.8
				9186.91	918691	100
Oyo	Bare area	406946	129773086	130	12977	0.5
	Built-up area	65719	183727541	184	18373	0.3
	Cropland	7046010	2082500154	2083	208250	3.8
	Forest	13133995	7900714923	7901	790071	14
	Grassland	7604805	3034884103	3035	303488	5.6
	Shrubland	20390673	14001863788	14002	1400186	26
	Water bodies	195076	61731668	27333	2733346	50
				54667	5466693	100

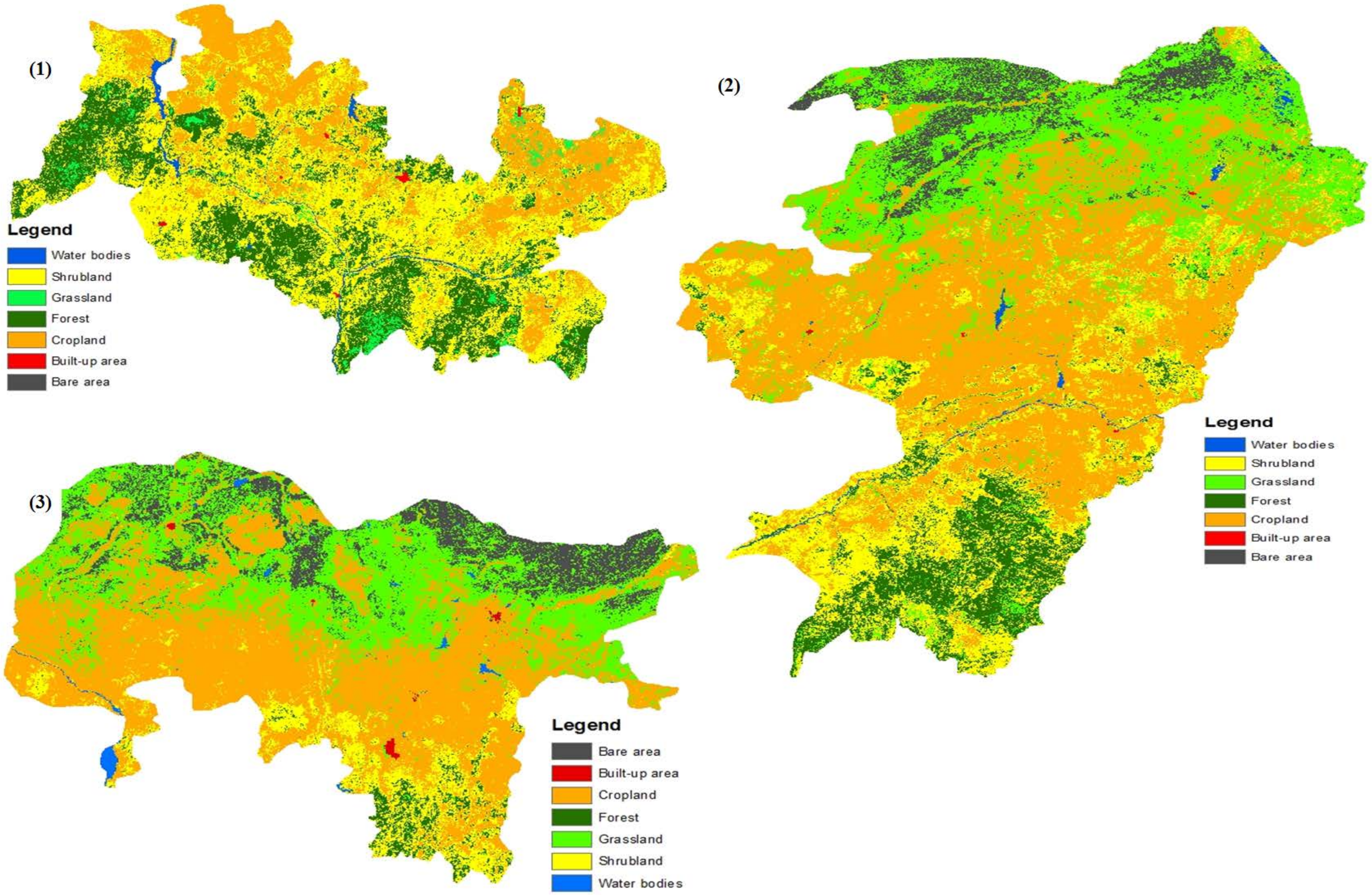
Appendix 15: The derived areas of Nigeria LC classes by state and FCT (continued).

State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Plateau	Bare area	39768	4511246	4.5	451	0.02
	Built-up area	44358	72699413	72.7	7270	0.3
	Cropland	16326372	17053970276	17054.0	1705397	61.8
	Forest	4447766	1331402658	1331.4	133140	4.8
	Grassland	4783234	1383776720	1383.8	138378	5.0
	Shrubland	16824263	7706348170	7706.3	770635	28
	Water bodies	115562	23480049	23.5	2348	0.1
				27576.2	2757619	100
Rivers	Bare area	1630	125568	0.13	12.6	0.001
	Cropland	24596	3233136	3.23	323.3	0.04
	Forest	7872248	2352227160	2352.23	235222.7	28
	Grassland	6250834	2038190880	2038.19	203819.1	24
	Shrubland	10871205	3203872130	3203.87	320387.2	38
	Water bodies	4131675	900748005	900.75	90074.8	11
				8498.40	849839.7	100
Sokoto	Bare area	16431137	6830068762	6830	683007	22
	Built-up area	35922	62407776	62	6241	0.2
	Cropland	12222174	10737192512	10737	1073719	34
	Grassland	27094173	13797078028	13797	1379708	43
	Shrubland	477124	143889813	144	14389	0.5
	Water bodies	297548	163169628	163	16317	0.5
				31734	3173381	100

Appendix 16: The derived areas of Nigeria LC classes by state and FCT (continued).

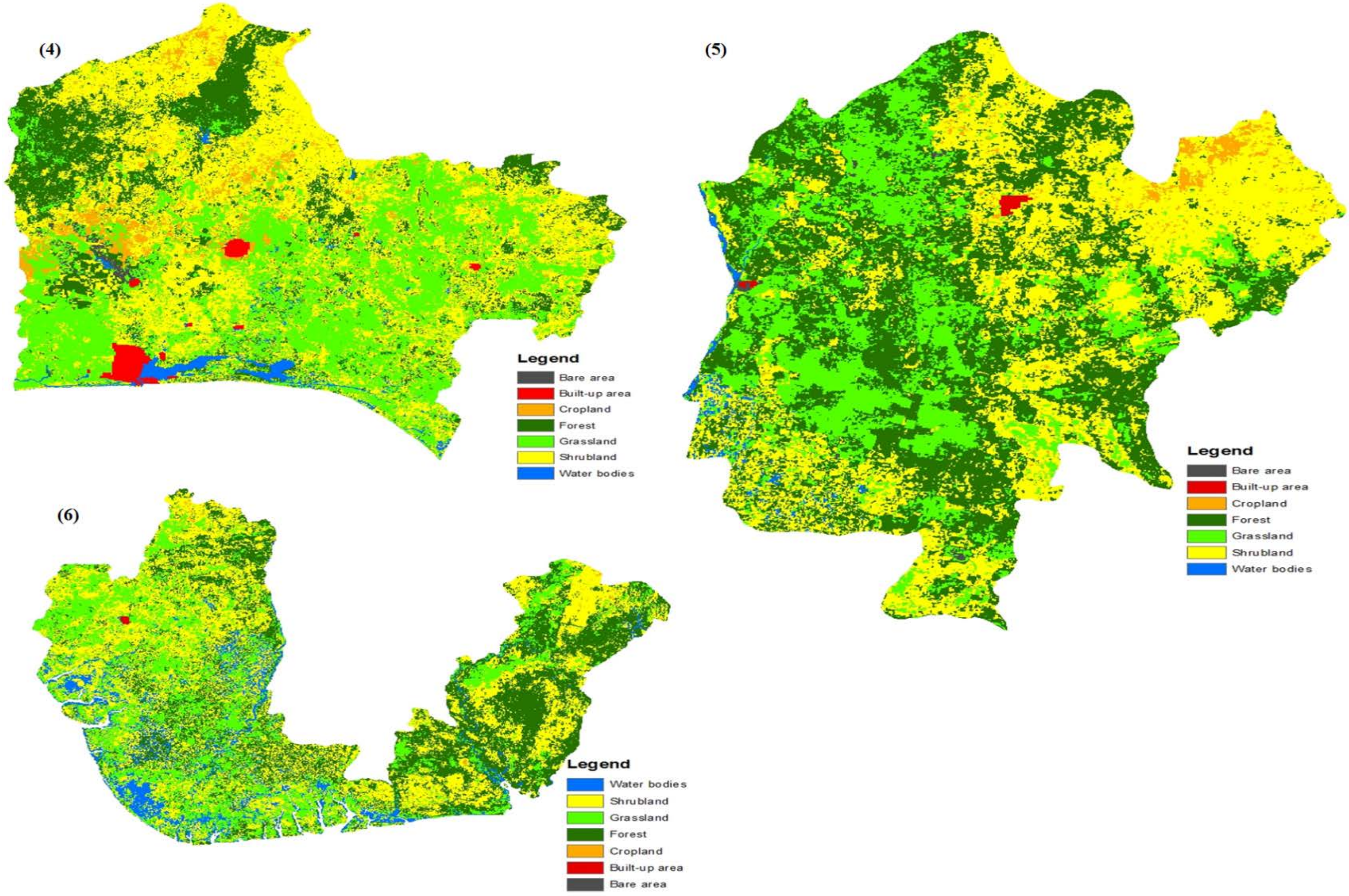
State	Land cover class	Length (m)	Area (m^2)	km^2	ha	%
Taraba	Bare area	450073	91478887	91.5	9148	0.2
	Cropland	20989606	13621610116	13621.6	1362161	23
	Forest	33164641	18316138574	18316.1	1831614	30
	Grassland	10365777	2472956904	2473.0	247296	4.1
	Shrubland	50036597	25223268187	25223.3	2522327	42
	Water bodies	1217723	362963781	363.0	36296	1
				60088.4	6008842	100
Water	Bare area	1430958	393411971	393	39341	7.6
	Cropland	2533569	744803358	745	74480	14
	Forest	715006	116619082	117	11662	2.2
	Grassland	5489878	3004827849	3005	300483	58
	Shrubland	2792683	620154891	620	62015	12
	Water bodies	819687	323882110	324	32388	6
				5204	520370	100
Yobe	Bare area	23148233	10151618215	10152	1015162	22
	Cropland	17932529	13737900704	13738	1373790	30
	Forest	115862	22658403	23	2266	0.05
	Grassland	39611724	20901110322	20901	2090111	46
	Shrubland	2757205	726756944	727	72676	1.6
	Water bodies	75050	15435624	15	1544	0.03
				45555	4555548	100
Zamfara	Bare area	6583946	3127576623	3128	312758	9.1
	Built-up area	18849	12598426	13	1260	0.04
	Cropland	13960713	18957426428	18957	1895743	55
	Forest	87809	13924304	14	1392	0.04
	Grassland	17823834	11464042388	11464	1146404	33
	Shrubland	2338636	832870333	833	83287	2.4
	Water bodies	379315	110287568	110	11029	0.3
				34519	3451873	100

Appendix 17: Land cover classes by the 6 Geopolitical zones of Nigeria



Numbers 1, 2 and 3 represent; North Central, North East, and North West Geopolitical zones respectively

Appendix 18: Land cover classes by the 6 Geopolitical zones of Nigeria



Numbers 4, 5 and 6 represent; South West, South East, and South South Geopolitical zones respectively

Appendix 19: Formatted maximum temperature by state for January 2010

States	**X**	**Y**	**Z**
Abakaliki (Ebonyi)	8.08	6.33	0
Abeokuta (Balogun et al)	3.33	7.2	35.3
Abuja (FCT)	7.48	9.07	35.3
Akure (Ondo)	5.19	7.25	33.3
Asaba (Delta)	6.198	6.198	35.5
Awka (Anambra)	7.068	6.207	35.5
Bauchi (Bauchi)	9.82	10.2	33.2
Benin	5.6	6.33	34.2
Calabar (Cross River)	8.35	4.97	33.9
Enugu (Enugu)	7.51	6.45	34.9
Gombe (Gombe)	11.17	10.2	33.1
Gusau (Zamfara)	6.67	12.15	33.5
Ibadan (Oyo)	3.9	7.39	34.3
Ibi, Taraba	9.44	8.1	36.6
Ikeja (Lagos)	3.33	6.58	42.9
Ilorin (Kwara)	4.58	8.48	36
Jos (Plateau)	8.9	9.87	28.7
Kaduna (Kaduna)	7.45	10.6	33.2
Kano (Kano)	8.53	12.05	32
Katsina (Katsina)	7.68	13.02	32
Lafia (Nassarawa)	8.5	8.55	37
Lokoja (Kogi)	6.73	7.8	35.9
Maiduguri (Borno)	13.08	11.85	33.9
Makurdi (Benue)	8.54	7.73	36.3
Minna (Niger)	6.54	9.56	36.4
Nguru (Yobe)	10.47	12.88	33
Oshogbo.	4.5	7.82	34.9
Owerri (Yano et al)	7.04	5.49	35.5
Port Harcourt (Rivers)	7.12	4.85	34.8
Sokoto (Sokoto)	5.2	12.92	35.2
Umuahia (Abia)	7.48	5.52	34.84
Uyo (Akwa Ibom)	7.92	5.05	34.7
Yelwa (Kebbi)	4.75	10.88	37.8
Yola (Adamawa)	12.47	9.23	36.6
Bida (Niger)	6	9.8	36.2
Ijebu Ode (Balogun et al)	3.93	6.83	33.5
Ogoja (Cross River)	8.8	6.7	36.7
Saki (Oyo)	3.47	8.35	34.8
Ondo (Ondo)	5.08	7.168	33.6

Appendix 20: Evaluation of suitability area for Switchgrass (*Panicum virgatum*) production in all the six geopolitical zones of Nigeria

Zone	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
NC	Not suitable	1332793	90000	1.19951E+11	119951.4	11995137	53	
	Marginally suitable	126377	90000	11373930000	11373.93	1137393	5	
	Moderately suitable	875855	90000	78826950000	78826.95	7882695	35	
	Highly suitable	184538	90000	16608420000	16608.42	1660842	7	
					226760.7	**22676067**	**100**	**106809.3**
NE	Not suitable	1771231	90000	1.59411E+11	159410.8	15941079	58	
	Marginally suitable	51568	90000	4641120000	4641.12	464112	2	
	Moderately suitable	1174188	90000	1.05677E+11	105676.9	10567692	39	
	Highly suitable	50190	90000	4517100000	4517.1	451710	2	
					274245.9	**27424593**	**100**	**114835.14**
NW	Not suitable	1449190	90000	1.30427E+11	130427.1	13042710	62	
	Moderately suitable	132705	90000	11943450000	11943.45	1194345	6	
	Highly suitable	773451	90000	69610590000	69610.59	6961059	33	
					211981.1	21198114	100	81554.04
SE	Not suitable	134276	90000	12084840000	12084.84	1208484	42	
	Moderately suitable	6	90000	540000	0.54	54	0	
	Highly suitable	181821	90000	16363890000	16363.89	1636389	58	
					28449.27	**2844927**	**100**	**16364.43**
SS	Not suitable	334396	90000	30095640000	30095.64	3009564	38	
	Moderately suitable	493343	90000	44400870000	44400.87	4440087	56	
	Highly suitable	53777	90000	4839930000	4839.93	483993	6	
					79336.44	**7933644**	**100**	**49240.8**
SW	Not suitable	219657	90000	19769130000	19769.13	1976913	26	
	Moderately suitable	33278	90000	2995020000	2995.02	299502	4	
	Highly suitable	579349	90000	52141410000	52141.41	5214141	70	
					74905.56	**7490556**	**100**	**55136.43**

Appendix 21: Evaluation of suitability area for the production of Miscanthus (*Miscanthus x giganteus*) in all the six geopolitical zones of Nigeria

Zones	Suitable class	Count	Cell size	m^2	Km^2	ha	%	Suitable area
NC	Not suitable	1332793	90000	1.19951E+11	119951	11995137	52.9	
	Moderately suitable	458777	90000	41289930000	41290	4128993	18.2	
	Highly suitable	727992	90000	65519280000	65519	6551928	28.9	
					226761	**22676058**	**100.0**	**106809**
NE	Not suitable	1771230	90000	1.59411E+11	159411	15941070	58.1	
	Moderately suitable	300	90000	27000000	27	2700	0.01	
	Highly suitable	1275646	90000	1.14808E+11	114808	11480814	41.9	
					274246	**27424584**	**100.0**	**114835**
NW	Not suitable	1465391	90000	1.31885E+11	131885	13188519	62.2	
	Moderately suitable	770023	90000	69302070000	69302	6930207	32.7	
	Highly suitable	119927	90000	10793430000	10793	1079343	5.1	
					211981	**21198069**	**100.0**	**80096**
SE	Not suitable	134274	90000	12084660000	12085	1208466	42.5	
	Marginally suitable	29997	90000	2699730000	2700	269973	9.5	
	Moderately suitable	151829	90000	13664610000	13665	1366461	48.0	
					28449	**2844900**	**100.0**	**16364**
SS	Not suitable	334396	90000	30095640000	30096	3009564	37.9	
	Marginally suitable	38258	90000	3443220000	3443	344322	4.3	
	Moderately suitable	494580	90000	44512200000	44512	4451220	56.1	
	Highly suitable	14282	90000	1285380000	1285	128538	1.6	
					79336	**7933644**	**100.0**	**49241**
SW	Not suitable	219657	90000	19769130000	19769	1976913	26.4	
	Moderately suitable	612086	90000	55087740000	55088	5508774	73.5	
	Highly suitable	539	90000	48510000	49	4851	0.1	
					74905	**7490538**	**100.0**	**55136**

Appendix 22: Evaluation of suitability area for the production of Elephant grass (*Pennisetum purpureum*) in all the six geopolitical zones of Nigeria

Zones	Suitable class	Count	Cell size	m^2	Km^2	ha	%	Suitable area
NC	Not suitable	1327512	90000	1.19476E+11	119476.1	11947608	52.9	
	Moderately suitable	160057	90000	14405130000	14405.13	1440513	6.4	
	Highly suitable	1021219	90000	91909710000	91909.71	9190971	40.7	
					225790.9	**22579092**	**100.0**	**106314.84**
NE	Not suitable	1731331	90000	1.5582E+11	155819.8	15581979	58.3	
	Moderately suitable	1065499	90000	95894910000	95894.91	9589491	35.9	
	Highly suitable	171595	90000	15443550000	15443.55	1544355	5.8	
					267158.3	**26715825**	**100.0**	**111338.46**
NW	Not suitable	1465391	90000	1.31885E+11	131885.2	13188519	62.2	
	Moderately suitable	708583	90000	63772470000	63772.47	6377247	30.1	
	Highly suitable	181367	90000	16323030000	16323.03	1632303	7.7	
					211980.7	**21198069**	**100.0**	**80095.5**
SE	Not suitable	134263	90000	12083670000	12083.67	1208367	42.5	
	Moderately suitable	156656	90000	14099040000	14099.04	1409904	49.6	
	Highly suitable	25161	90000	2264490000	2264.49	226449	8.0	
					28447.2	**2844720**	**100.0**	**16363.53**
SS	Not suitable	329966	90000	29696940000	29696.94	2969694	37.8	
	Moderately suitable	308959	90000	27806310000	27806.31	2780631	35.4	
	Highly suitable	234072	90000	21066480000	21066.48	2106648	26.8	
					78569.73	**7856973**	**100.0**	**48872.79**
SW	Not suitable	219657	90000	19769130000	19769.13	1976913	26.4	
	Moderately suitable	86	90000	7740000	7.74	774	0.0	
	Highly suitable	612539	90000	55128510000	55128.51	5512851	73.6	
					74905.38	**7490538**	**100.0**	**55136.25**

Appendix 23: Evaluation of suitability area for the production of Alfalfa (*Medicago sativa*) in all the six geopolitical zones of Nigeria

Zones	Suitable class	Count	Cell size	m^2	Km^2	ha	%	Suitable area
NC	Not suitable	1332793	90000	1.19951E+11	119951.4	11995137	52.9	
	Moderately suitable	10577	90000	951930000	951.93	95193	0.4	
	Highly suitable	1176192	90000	1.05857E+11	105857.3	10585728	46.7	
					226760.6	**22676058**	**100.0**	**106809.21**
NE	Not suitable	1771230	90000	1.59411E+11	159410.7	15941070	58.1	
	Moderately suitable	177195	90000	15947550000	15947.55	1594755	5.8	
	Highly suitable	1098751	90000	98887590000	98887.59	9888759	36.1	
					274245.8	**27424584**	**100.0**	**114835.14**
NW	Not suitable	1465338	90000	1.3188E+11	131880.4	13188042	62.2	
	Moderately suitable	43124	90000	3881160000	3881.16	388116	1.8	
	Highly suitable	846702	90000	76203180000	76203.18	7620318	36.0	
					211964.8	**21196476**	**100.0**	**80084.34**
SE	Not suitable	134274	90000	12084660000	12084.66	1208466	42.5	
	Highly suitable	181826	90000	16364340000	16364.34	1636434	57.5	
					28449	**2844900**	**100.0**	**16364.34**
SS	Not suitable	334396	90000	30095640000	30095.64	3009564	37.9	
	Moderately suitable	7553	90000	679770000	679.77	67977	0.9	
	Highly suitable	539567	90000	48561030000	48561.03	4856103	61.2	
					79336.44	**7933644**	**100.0**	**49240.8**
SW	Not suitable	219657	90000	19769130000	19769.13	1976913	26.4	
	Moderately suitable	15773	90000	1419570000	1419.57	141957	1.9	
	Highly suitable	596852	90000	53716680000	53716.68	5371668	71.7	
					74905.38	**7490538**	**100.0**	**55136.25**

Appendix 24: Evaluating the most suitable zone for the selected species

Zone	AG	SG	MG	EG	Total
NC	106809.2	106809.3	106809	106314	**4267415**
NE	114835.3	114835.1	114835	111338.5	**45584389**
NW	80084.34	81554.04	80096	80095.5	**32182988**
SE	16364.34	1634.43	16364	16363.53	**6545687**
SS	49240.8	49240.8	49241	55136.25	**20875385**
SW	55136.25	55136.34	55136	55136.25	**22054484**

Appendix 25: Evaluation of the most suitable state in Nigeria for Alfalfa (*Medicago sativa*) production in the NE geopolitical zone of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Adamawa	Not suitable	259890	90000	23390100000	23390.1	2339010	70.96	
	Moderately suitable	34899	90000	3140910000	3140.91	314091	9.53	
	Highly suitable	71434	90000	6429060000	6429.06	642906	19.51	
					32960.07	**3296007**	**100.00**	**9569.97**
Bauchi	Not suitable	355198	90000	31967820000	31967.82	3196782	65.25	
	Moderately suitable	15125	90000	1361250000	1361.25	136125	2.78	
	Highly suitable	174078	90000	15667020000	15667.02	1566702	31.98	
					48996.09	**4899609**	**100.00**	**17028.27**
Borno	Not suitable	355331	90000	31979790000	31979.79	3197979	48.94	
	Moderately suitable	33631	90000	3026790000	3026.79	302679	4.63	
	Highly suitable	337045	90000	30334050000	30334.05	3033405	46.42	
					65340.63	**6534063**	**100.00**	**33360.84**
Gombe	Not suitable	169768	90000	15279120000	15279.12	1527912	83.99	
	Moderately suitable	6985	90000	628650000	628.65	62865	3.46	
	Highly suitable	25365	90000	2282850000	2282.85	228285	12.55	
					18190.62	**1819062**	**100.00**	**2911.50**
Taraba	Not suitable	353628	90000	31826520000	31827	3182700	53.92	
	Moderately suitable	63448	90000	5710320000	5710	571000	9.67	
	Highly suitable	238810	90000	21492900000	21493	2149300	36.41	
					59030	**5903000**	**100.00**	**27203.00**
Yobe	Not suitable	260503	90000	23445270000	23445.27	2344527	52.36	
	Moderately suitable	1834	90000	165060000	165.06	16506	0.37	
	Highly suitable	235214	90000	21169260000	21169.26	2116926	47.27	
					44779.59	**4477959**	**100.00**	**21334.32**
water	Not suitable	16877	90000	1518930000	1518.93	151893	30.71	
	Moderately suitable	21276	90000	1914840000	1914.84	191484	38.71	
	Highly suitable	16806	90000	1512540000	1512.54	151254	30.58	
					4946.31	**494631**	**100.00**	**3427.38**

Appendix 26: Evaluation of the most suitable state in Nigeria for Switchgrass (*Panicum virgatum*) production in the NE geopolitical zone of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Adamawa	Not suitable	259890	90000	2.34E+10	23390.1	2339010	70.96	
	Marginally suitable	2659	90000	2.39E+08	239.31	23931	0.73	
	Highly suitable	103674	90000	9.33E+09	9330.66	933066	28.31	
					32960.07	**3296007**	**100.00**	**9569.97**
Bauchi	Not suitable	355198	90000	3.2E+10	31967.82	3196782	65.25	
	Marginally suitable	1914	90000	1.72E+08	172.26	17226	0.35	
	Highly suitable	187289	90000	1.69E+10	16856.01	1685601	34.40	
					48996.09	**4899609**	**100.00**	**17028.27**
Borno	Not suitable	355331	90000	3.2E+10	31979.79	3197979	48.94	
	Moderately suitable	342037	90000	3.08E+10	30783.33	3078333	47.11	
	Highly suitable	28639	90000	2.58E+09	2577.51	257751	3.94	
					65340.63	**6534063**	**100.00**	**33360.84**
Gombe	Not suitable	169768	90000	1.53E+10	15279.12	1527912	83.99	
	Moderately suitable	32350	90000	2.91E+09	2911.5	291150	16.01	
					18190.62	**1819062**	**100.00**	**2911.5**
Taraba	Not suitable	353629	90000	3.18E+10	31826.61	3182661	53.92	
	Marginally suitable	46995	90000	4.23E+09	4229.55	422955	7.17	
	Highly suitable	255263	90000	2.3E+10	22973.67	2297367	38.92	
					59029.83	**5902983**	**100.00**	**27203.22**
Water	Not suitable	16881	90000	1.52E+09	1519.29	151929	30.71	
	Moderately suitable	16804	90000	1.51E+09	1512.36	151236	30.57	
	Highly suitable	21279	90000	1.92E+09	1915.11	191511	38.71	
					4946.76	494676	100.00	3427.47
Yobe	Not suitable	260503	90000	2.34E+10	23445.27	2344527	52.36	
	Moderately suitable	236771	90000	2.13E+10	21309.39	2130939	47.59	
	Highly suitable	277	90000	24930000	24.93	2493	0.06	
					44779.59	4477959	100.00	21334.32

Appendix 27: Evaluation of the most suitable state in Nigeria for *Miscanthus x giganteus* production in the NE geopolitical zone of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Adamawa	Not suitable	259890	90000	2.34E+10	23390.1	2339010	71.00	
	Moderately suitable	300	90000	27000000	27	2700	0.00	
	Highly suitable	106033	90000	9.54E+09	9542.97	954297	29.00	
					32960.07	**3296007**	**100.00**	**9569.97**
Bauchi	Not suitable	355198	90000	3.2E+10	31967.82	3196782	65.25	
	Highly suitable	189203	90000	1.7E+10	17028.27	1702827	34.75	
					48996.09	**4899609**	**100.00**	**17028.27**
Borno	Not suitable	355331	90000	3.2E+10	31979.79	3197979	48.94	
	Highly suitable	370676	90000	3.34E+10	33360.84	3336084	51.06	
					65340.63	**6534063**	**100.00**	**33360.84**
Gombe	Not suitable	169768	90000	1.53E+10	15279.12	15279.12	83.99	
	Highly suitable	32350	90000	2.91E+09	2911.5	2911.5	16.01	
					18190.62	**18190.62**	**100.00**	**2911.5**
Taraba	Not suitable	353628	90000	3.18E+10	31826.52	3182652	53.92	
	Highly suitable	302258	90000	2.72E+10	27203.22	2720322	46.08	
							100.00	**27203.22**
Water	Not suitable	16881	90000	1.52E+09	1519.29	151929	30.71	
	Highly suitable	38083	90000	3.43E+09	3427.47	342747	69.29	
					4946.76	**494676**	**100.00**	**3427.47**
Yobe	Not suitable	260503	90000	2.34E+10	23445.27	2344527	52.36	
	Highly suitable	237048	90000	2.13E+10	21334.32	2133432	47.64	
					44779.59	**4477959**	**100.00**	**21334.32**

Appendix 28: Evaluation of the most suitable state in Nigeria for Elephant grass (*Pennisetum purpureum*) production in the NE geopolitical zone of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Adamawa	Not suitable	250143	90000	2.25E+10	22512.87	2251287	71.81	
	Moderately suitable	97834	90000	8.81E+09	8805.06	880506	28.09	
	Highly suitable	353	90000	31770000	31.77	3177	0.10	
					31349.7	**3134970**	**100.00**	**8836.83**
Bauchi	Not suitable	353563	90000	3.18E+10	31820.67	3182067	65.33	
	Moderately suitable	170949	90000	1.54E+10	15385.41	1538541	31.59	
	Highly suitable	16677	90000	1.5E+09	1500.93	150093	3.08	
					48707.01	**4870701**	**100.00**	**16886.34**
Borno	Not suitable	354383	90000	3.19E+10	31894.47	3189447	48.91	
	Moderately suitable	370133	90000	3.33E+10	33311.97	3331197	51.09	
							100.00	**33311.97**
Gombe	Not suitable	168739	90000	1.52E+10	15186.51	1518651	84.30	
	Moderately suitable	31419	90000	2.83E+09	2827.71	282771	15.70	
							100.00	**2827.71**
Taraba	Not suitable	327091	90000	2.94E+10	29438.19	2943819	54.36	
	Moderately suitable	120046	90000	1.08E+10	10804.14	1080414	19.95	
	Highly suitable	154564	90000	1.39E+10	13910.76	1391076	25.69	
					54153.09	**5415309**	**100.00**	**24714.9**
Water	Not suitable	16881	90000	1.52E+09	1519.29	151929	30.71	
	Moderately suitable	38083	90000	3.43E+09	3427.47	342747	69.29	
					4946.76	**494676**	**100.00**	**3427.47**
Yobe	Not suitable	260503	90000	2.34E+10	23445.27	2344527	52.36	
	Moderately suitable	237041	90000	2.13E+10	21333.69	2133369	47.64	
							100.00	**21333.69**

Appendix 29: Evaluation of the most suitable state in Nigeria for Alfalfa (*Medicago sativa*) production in the SW geopolitical zone of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m²**	**Km²**	**ha**	**%**	Suitable area
Ekiti	Not suitable	9281	90000	8.35E+08	835.29	83529	15.99	
	Moderately suitable	3483	90000	3.13E+08	313.47	31347	6.00	
	Highly suitable	45295	90000	4.08E+09	4076.55	407655	78.02	
					5225.31	**522531**	**100.00**	**4390.02**
Lagos	Not suitable	19146	90000	1.72E+09	1723.14	172314	52.20	
	Highly suitable	17535	90000	1.58E+09	1578.15	157815	47.80	
					3301.29	**330129**	**100.00**	**1578.15**
Ogun	Not suitable	36988	90000	3.33E+09	3328.92	332892	21.19	
	Moderately suitable	262	90000	23580000	23.58	2358	0.15	
	Highly suitable	137343	90000	1.24E+10	12360.87	1236087	78.66	
					15713.37	**1571337**	**100.00**	**12384.45**
Ondo	Not suitable	22764	90000	2.05E+09	2048.76	204876	14.35	
	Moderately suitable	993	90000	89370000	89.37	8937	0.63	
	Highly suitable	134865	90000	1.21E+10	12137.85	1213785	85.02	
					14275.98	**1427598**	**100.00**	**12227.22**
Osun	Not suitable	16302	90000	1.47E+09	1467.18	146718	15.98	
	Moderately suitable	4057	90000	3.65E+08	365.13	36513	3.98	
	Highly suitable	81686	90000	7.35E+09	7351.74	735174	80.05	
					9184.05	**918405**	**100.00**	**7716.87**
Oyo	Not suitable	115162	90000	1.04E+10	10364.58	1036458	38.10	
	Moderately suitable	6978	90000	6.28E+08	628.02	62802	2.31	
	Highly suitable	180109	90000	1.62E+10	16209.81	1620981	59.59	
					27202.41	**2720241**	**100.00**	**16837.83**

Appendix 30: Evaluation of the most suitable state in Nigeria for Switchgrass (*Panicum virgatum*) production in the SW geopolitical zone of Nigeria.

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Ekiti	Not suitable	9281	90000	8.35E+08	835.29	83529	15.99	
	Moderately suitable	6926	90000	6.23E+08	623.34	62334	11.93	
	Highly suitable	41852	90000	3.77E+09	3766.68	376668	72.09	
					5225.31	**522531**	**100.00**	**4390.02**
lagos	Not suitable	19146	90000	1.72E+09	1723.14	172314	52.20	
	Moderately suitable	369	90000	33210000	33.21	3321	1.01	
	Highly suitable	17166	90000	1.54E+09	1544.94	154494	46.80	
					3301.29	**330129**	**100.00**	**1578.15**
Ogun	Not suitable	36988	90000	3.33E+09	3328.92	332892	21.19	
	Moderately suitable	3361	90000	3.02E+08	302.49	30249	1.93	
	Highly suitable	134244	90000	1.21E+10	12081.96	1208196	76.89	
					15713.37	**1571337**	**100.00**	**12384.45**
Ondo	Not suitable	22764	90000	2.05E+09	2048.76	204876	14.35	
	Moderately suitable	16733	90000	1.51E+09	1505.97	150597	10.55	
	Highly suitable	119127	90000	1.07E+10	10721.43	1072143	75.10	
					14276.16	**1427616**	**100.00**	**12227.4**
Osun	Not suitable	16302	90000	1.47E+09	1467.18	146718	15.98	
	Moderately suitable	5606	90000	5.05E+08	504.54	50454	5.49	
	Highly suitable	80137	90000	7.21E+09	7212.33	721233	78.53	
					9184.05	**918405**	**100.00**	**7716.87**
Oyo	Not suitable	115162	90000	1.04E+10	10364.58	1036458	38.10	
	Moderately suitable	283	90000	25470000	25.47	2547	0.09	
	Highly suitable	186804	90000	1.68E+10	16812.36	1681236	61.80	
					27202.41	**2720241**	**100.00**	**16837.83**

Appendix 31: Evaluation of the most suitable state in Nigeria for *Miscanthus giganteus* production in the South of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m^2**	**Km^2**	**ha**	**%**	Suitable area
Ekiti	Not suitable	9284	90000	8.36E+08	835.56	83556	15.99	
	Moderately suitable	48775	90000	4.39E+09	4389.75	438975	84.01	
					5225.31	522531	100.00	4389.75
Lagos	Not suitable	19139	90000	1.72E+09	1722.51	172251	52.21	
	Moderately suitable	17520	90000	1.58E+09	1576.8	157680	47.79	
					3299.31	329931	100.00	1576.8
Ogun	Not suitable	36991	90000	3.33E+09	3329.19	332919	21.19	
	Moderately suitable	137478	90000	1.24E+10	12373.02	1237302	78.74	
	Highly suitable	134	90000	12060000	12.06	1206	0.08	
					15714.27	1571427	100.00	12385.08
Ondo	Not suitable	22774	90000	2.05E+09	2049.66	204966	14.36	
	Moderately suitable	135465	90000	1.22E+10	12191.85	1219185	85.40	
	Highly suitable	389	90000	35010000	35.01	3501	0.25	
					14276.52	1427652	100.00	12226.86
Osun	Not suitable	16300	90000	1.47E+09	1467	146700	15.97	
	Moderately suitable	85720	90000	7.71E+09	7714.8	771480	84.01	
	Highly suitable	15	90000	1350000	1.35	135	0.01	
					9183.15	918315	100.00	7716.15
Oyo	Not suitable	115162	90000	1.04E+10	10364.58	1036458	38.10	
	Moderately suitable	187108	90000	1.68E+10	16839.72	1683972	61.90	
					27204.3	2720430	100.00	16839.72

Appendix 32: Evaluation of the most suitable state for Elephant grass (*Pennisetum purpureum*) production in the South of Nigeria

State	**Suitability class**	**Count**	**Cell size**	**m²**	**Km²**	**ha**	**%**	Suitable area
Ekiti	Not suitable	9281	90000	8.35E+08	835.29	83529	15.99	
	Moderately suitable	1	90000	90000	0.09	9	0.00	
	Highly suitable	48777	90000	4.39E+09	4389.93	438993	84.01	
					5225.31	**522531**	**100.00**	**4390.02**
Lagos	Not suitable	19146	90000	1.72E+09	1723.14	172314	52.20	
	Highly suitable	17535	90000	1.58E+09	1578.15	157815	47.80	
					3301.29	**330129**	**100.00**	**1578.15**
Ogun	Not suitable	36988	90000	3.33E+09	3328.92	332892	21.19	
	Highly suitable	137605	90000	1.24E+10	12384.45	1238445	78.81	
					15713.37	**1571337**	**100.00**	**12384.45**
Ondo	Not suitable	22764	90000	2.05E+09	2048.76	204876	14.3511	
	Highly suitable	135858	90000	1.22E+10	12227.22	1222722	85.6489	
					14275.98	**1427598**	**100.00**	**12227.22**
Osun	Not suitable	16302	90000	1.47E+09	1467.18	146718	15.98	
	Moderately suitable	7	90000	630000	0.63	63	0.01	
	Highly suitable	85736	90000	7.72E+09	7716.24	771624	84.02	
					9184.05	**918405**	**100.00**	**7716.87**
Oyo	Not suitable	115162	90000	1.04E+10	10364.58	1036458	38.10	
	Moderately suitable	78	90000	7020000	7.02	702	0.03	
	Highly suitable	187009	90000	1.68E+10	16830.81	1683081	61.87	
					27202.41	**2720241**	**100.00**	**16837.83**

Appendix 33: Evaluating the most suitable state for the AG, EG, MG and SG species in the Southern Nigeria (Oyo state)

State	**AG**	**EG**	**MG**	**SG**
Ekiti	4390.02	4390	4390	4390.02
Lagos	1578.15	1578	1577	1578.15
Ogun	12384.45	12385	12385	12384.45
Ondo	12227.22	12227.22	12227	12227.4
Osun	7716.87	7717	7716	7716.87
Oyo	16837.83	16838	16840	16837.83

Appendix 34: Evaluating the most suitable state for the AG, EG, MG and SG species in the Northern Nigeria (Borno state)

State	**AG**	EG	MG	SG
Adamawa	9569.97	8836.83	9569.97	9569.97
Bauchi	17028.27	16886.34	17028.27	17028.27
Borno	33360.84	33311.97	33360.84	33360.84
Gombe	2911.5	2827.71	2911.5	2911.5
Taraba	27203	24714.9	27203.22	27203.22
Yobe	21334.32	21333.69	21334.32	21334.32
Chad basin	3427.38	3427.47	3427.47	3427.47

Appendix 35: Estimated yield of alfalfa (AG) productivity in the six geopolitical zones of Nigeria.

SW							
Prod. class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Suitable areas (%)	tonnes/ha
Low	18	219657	3953826	7.00	1976913	26	2.00
Medium	41	15773	646693	1.00	141957	2	4.56
High	90	596852	53716680	92	5371668	72	10.00
Total			**58317199**	**100**	**7490538**	100	**7.79**
SS							
Low	18	334396	6019128	11	3009564	38	2.00
Medium	41	7553	309673	1	67977	0.9	4.56
High	90	539567	48561030	88	4856103	61	10.00
Total			**54889831**	**100**	**7933644**	100	**6.92**
SE							
Low	18	134274	2416932	13	1208466	42	2.00
High	90	181826	16364340	87	1636434	58	10.00
Total			**18781272**	**100**	**2844900**	100	**6.60**
NW							
Low	18	1465338	26376084	25	13188042	62	2.00
Medium	41	43124	1768084	2	388116	1.8	4.56
High	90	846702	76203180	73	7620318	36	10.00
Total			**104347348**	**100**	**21196476**	100	**4.92**
NE							
Low	18	1771230	31882140	23	15941070	58	2.00
Medium	41	177195	7264995	5	1594755	5.8	4.56
High	90	1098751	98887590	72	9888759	36.1	10.00
Total			**138034725**	**100**	**27424584**	100.0	**5.03**
NC							
Low	18	1332793	23990274	18	11995137	53	2.00
Medium	41	10577	433657	0.3	95193	0.4	4.56
High	90	1176192	105857280	81	10585728	46.7	10.00
Total			**130281211**	**100**	**22676058**	100	**5.75**

Appendix 36: Estimated yield of MG productivity in the six geopolitical zones of Nigeria.

NC							
Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable areas (ha)	Areas (%)	Yield (tonnes/ha)
Low	27	1332793	35985411	14.00	11995137	53	3.00
Medium	162	458777	74321874	29.00	4128993	18	18.00
High	198	727992	144142416	57.00	6551928	29	22.00
Total			**254449701**	**100.00**	**22676058**	100	**11.22**
NE							
Low	27	1771230	47823210	15.92	15941070	58	3.00
Medium	162	300	48600	0.02	2700	0	18.00
High	198	1275646	252577908	84.07	11480814	42	22.00
Total			**300449718**	**100.00**	**27424584**	100	**10.96**
NW							
Low	27	1465391	39565557	21.00	13188519	62	3.00
Medium	162	770023	124743726	66.00	6930207	33	18.00
High	198	119927	23745546	13.00	1079343	5	22.00
Total			**188054829**	**100.00**	**21198069**	100	**8.87**
SE							
Low	27	134274	3625398	9	1208466	42.478	3.00
Medium	162	29997	4859514	13	269973	9.4897	18.00
High	198	151829	30062142	78	1366461	48.032	22.00
Total			**38547054**	**100.00**	**2844900**	100	**13.55**
SS							
Low	27	334396	9028692	9.00	3009564	37.934	3.00
Medium	162	494580	80121960	80.00	4795542	60.4	16.71
High	198	52540	10402920	10.00	128538	1.6202	80.93
Total			**99553572**	**99.00**	**7933644**	100	**12.55**
SW							
Low	27	219657	5930739	5.64	1976913	26.392	3.00
Medium	162	612086	99157932	94.26	5508774	73.543	18.00
High	198	539	106722	0.10145	4851	0.0648	22.00
Total			**105195393**	**100.00**	**7490538**	100	**14.04**

Appendix 37: Estimated yield of SG productivity in the six geopolitical zones of Nigeria.

NE							
Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable areas (ha)	Area (%)	Yield (tonnes/ha)
Low	18	1771231	31882158	16	15941079	58	2.00
Medium	126	1174188	147947688	75	11031804	40	13.41
High	171	101758	17400618	9	451710	2	38.52
Total			**197230464**	**100**	**27424593**	100	7.19
NC							
Low	18	1332793	23990274	13	11995137	53	2.00
Medium	126	875855	110357730	59	9020088	40	12.23
High	171	310915	53166465	28	1660842	7	32.01
Total			**187514469**	**100**	**22676067**	100	8.27
NW							
Low	18	1449190	26085420	18	**13042710**	62	2.00
Medium	126	773451	97454826	67	**1194345**	6	81.60
High	171	132705	22692555	15	**6961059**	33	3.26
Total			**146232801**	**100**	**21198114**	100	6.90
SE							
Low	18	134276	2416968	7.2	1208500	42	2.00
Medium	126	6	756	0.002	100	0.00	7.56
High	171	181821	31091391	93	1636400	58	19.00
Total			**33509115**	**100**	**2845000**	100	11.78
SS							
Low	18	334396	6019128	8	3009564	38	2.00
Medium	126	493343	62161218	80	4440087	56	14.00
High	171	53777	9195867	12	483993	6.1	19.00
Total			**77376213**	**100**	**7933644**	100	9.75
SW							
Low	18	219657	3953826	4	1976913	26	2.00
Medium	126	33278	4193028	4	299502	4	14.00
High	171	579349	99068679	92	5214141	70	19.00
Total			**107215533**	**100**	**7490556**	100	14.31

Appendix 38: Estimated yield of EG productivity in the six geopolitical zones of Nigeria.

NW							
Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	tonnes/ha
Low	64	1465391	93785024	35	13188519	62	7.11
Medium	177	708583	125419191	47	6377247	30	19.67
High	271	181367	49150457	18	1632303	8	30.11
Total			**268354672**	**100**	**21198069**	100	**12.66**
NE							
Low	64	1731331	110805184	32	15581979	58	7.11
Medium	177	1065499	188593323	55	9589491	36	19.67
High	271	171595	46502245	13	1544355	6	30.11
Total			**345900752**	**100**	**26715825**	100	12.95
NC							
Low	64	1327512	84960768	22	11947608	53	7.11
Medium	177	160057	28330089	7	1440513	6	19.67
High	271	1021219	276750349	71	9190971	41	30.11
Total			**390041206**	**100**	**22579092**	100	17.27
SE							
Low	64	134263	8592832	20	1208367	42	7.11
Medium	177	156656	27728112	64	1409904	50	19.67
High	271	25161	6818631	16	226449	8	30.11
Total			**43139575**	**100**	**2844720**	100	15.16
SS							
Low	64	329966	21117824	15	2969694	38	7.11
Medium	177	308959	54685743	39	2780631	35	19.67
High	271	234072	63433512	46	2106648	27	30.11
Total			**139237079**	**100**	**7856973**	100	17.72
SW							
Low	64	219657	14058048	8	1976913	26	7.11
Medium	177	86	15222	0	774	0	19.67
High	271	612539	165998069	92	5512851	74	30.11
Total			**180071339**	**100**	**7490538**	100	24.04

Appendix 39: Estimation of the most productive state for growing AG in the North of Nigeria

Adamawa							
Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Low	18	259890	4678020	37.31	2339010	71.0	2.00
Medium	41	34899	1430859	11.41	314091	9.5	4.56
High	90	71434	6429060	51.28	642906	19.5	10.00
Total			**12537939**	**100.00**	**3296007**	100.0	3.80
Bauchi							
Low	18	355198	6393564	28.00	3196782	65.2	2.00
Medium	41	15125	620125	3.00	136125	2.8	4.56
High	90	174078	15667020	69.00	1566702	32.0	10.00
Total			**22680709**	**100.00**	**4899609**	100.0	4.63
Borno							
Low	18	355331	6395958	16.78	3197979	48.9	2
Medium	41	33631	1378871	3.62	302679	4.6	4.56
High	90	337045	30334050	79.60	3033405	46.4	10.00
Total			**38108879**	**100.00**	**6534063**	100.0	5.83
Gombe							
Low	18	169768	3055824	54.33	1527912	84.0	2.00
Medium	41	6985	286385	5.09	62865	3.5	4.56
High	90	25365	2282850	40.58	228285	12.5	10.00
Total			**5625059**	**100.00**	**1819062**	100.0	3.09
Taraba							
Low	18	353628	6365304	20.90	3182700	53.9	2.00
Medium	41	63448	2601368	8.54	571000	9.7	4.56
High	90	238810	21492900	70.56	2149300	36.4	10.00
Total			**30459572**	**100.00**	**5903000**	100.0	5.16
Yobe							
Low	18	260503	4689054	18.08	2344527	52.4	2.00
Medium	41	1834	75194	0.29	16506	0.4	4.56
High	90	235214	21169260	81.63	2116926	47.3	10.00
Total			**25933508**	**100**	**4477959**	100.0	5.79
Water							
Low	18	16877	303786	11.30	151893	30.7	2.00
Medium	41	21276	872316	32.44	191484	38.7	4.56
High	90	16806	1512540	56.26	151254	30.6	10.00
Total			**2688642**	**100.00**	**494631**	100.0	5.44

Appendix 40: Estimation of the most productive state for growing Elephant grass (EG) in across the Northern Nigeria.

Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Adamawa							
Low	64	250143	16009152	47.90	2251287	71.8	7.11
Medium	177	97834	17316618	51.81	880506	28.1	19.67
High	271	353	95663	0.29	3177	0.1	30.11
Total			**33421433**	**100.00**	**3134970**	100.0	10.66
Bauchi							
Low	64	353563	22628032	39.00	3182067	65.3	7.11
Medium	177	170949	30257973	53.00	1538541	31.6	19.67
High	271	16677	4519467	8.00	150093	3.1	30.11
Total			**57405472**	**100.00**	**4870701**	100.0	11.79
Borno							
Low	64	354383	22680512	26.00	3189447	48.9	7.11
Medium	177	370133	65513541	74.00	3331197	51.1	19.67
Total			**88194053**	**100.00**	**6520644**	100.0	13.53
Gombe							
Low	64	168739	10799296	66.00	1518651	84.3	7.11
Medium	177	31419	5561163	34.00	282771	15.7	19.67
Total			**16360459**	**100.00**	**1801422**	100.0	9.08
Taraba							
Low	64	327091	20933824	24.90	2943819	54.4	7.11
Medium	177	120046	21248142	25.27	1080414	20.0	19.67
High	271	154564	41886844	49.82	1391076	25.7	30.11
Total			**84068810**	**100.00**	**5415309**	100.0	15.52
Yobe							
Low	64	260503	16672192	28.00	2344527	52.4	7.11
Medium	177	237041	41956257	72.00	2133369	47.6	19.67
Total			**58628449**	**100.00**	**4477896**	100.0	13.09
Water							
Low	64	16881	1080384	14.00	151929	31	7.11
Medium	177	38083	6740691	86.00	342747	69	19.67
Total			**7821075**	**100.00**	**494676**	100	15.81

Appendix 41: Estimation of the most productive state for growing *Miscanthus x giganteus* in across the Northern Nigeria.

Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Adamawa							
Low	27	259890	7017030	25.0	2339010	71.0	3.00
Medium	162	300	48600	0.2	2700	0.0	18.00
High	198	106033	20994534	74.8	954297	29.0	22.00
Total			**28060164**	**100.0**	**3296007**	100.0	8.51
Bauchi							
Low	27	355198	9590346	20.0	3196782	65.2	3.00
High	198	189203	37462194	80.0	1702827	34.8	22.00
Total			**47052540**	**100.0**	**4899609**	100.0	9.60
Borno							
Low	27	355331	9593937	12.0	3197979	48.9	3.00
High	198	370676	73393848	88.0	3336084	51.1	22.00
Total			**82987785**	**100.0**	**6534063**	100.0	12.70
Gombe							
Low	27	169768	4583736	42.0	1527912	84.0	3.00
High	198	32350	6405300	58.0	291150	16.0	22.00
Total			**10989036**	**100.0**	**1819062**	100.0	6.04
Taraba							
Low	27	353628	9547956	14.0	3182652	53.9	3.00
High	198	302258	59847084	86.0	2720322	46.1	22.00
Total			**69395040**	**100.0**	**5902974**	100.0	11.76
Yobe							
Low	27	260503	7033581	13.0	2344527	52.4	3.00
High	198	237048	46935504	87.0	2133432	47.6	22.00
Total			**53969085**	**100.0**	**4477959**	100.0	12.05
Water							
Low	27	16881	455787	6.0	151929	30.7	3.00
High	198	38083	7540434	94.0	342747	69.3	22.00
Total			**7996221**	**100.0**	**494676**	100.0	16.16

Appendix 42: Estimation of the most productive state for growing SG across the Northern Nigeria

Productivity class	Yield (tonnes)	count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Adamawa							
Low	18	259890	4678020	19.00	2339010	71	2
Medium	126	2659	335034	1.00	23931	0.7	14
High	189	103674	19594386	80.00	933066	28	21
Total			**24607440**	**100.00**	**3296007**	100	7.5
Bauchi							
Low	18	355198	6393564	15.00	3196782	65	2
Medium	126	1914	241164	1.00	17226	0.4	14
High	189	187289	35397621	84.00	1685601	34	21
Total			**42032349**	**100.00**	**4899609**	100	8.6
Borno							
Low	18	355331	6395958	12.00	3197979	49	2
Medium	126	342037	43096662	78.00	3078333	47	14
High	189	28639	5412771	10.00	257751	3.9	21
Total			**54905391**	**100.00**	**6534063**	100	8.4
Gombe							
Low	18	169768	3055824	43.00	1527912	84	2
Medium	126	32350	4076100	57.00	291150	16	14
Total			**7131924**	**100.00**	**1819062**	100	3.9
Taraba							
Low	18	353629	6365322	13.00	**3182661**	54	2
Medium	126	255263	32163138	68.00	**422955**	7.2	76.
High	189	46995	8882055	19.00	**2297367**	39	3.9
Total			**47410515**	**100.00**	**5902983**	100	8.0
Yobe							
Low	18	260503	4689054	13.56	2344527	52.35705	2
Medium	126	236771	29833146	86.29	2130939	47.58728	14
High	189	277	52353	0.15	2493	0.055673	21
Total			**34574553**	**100.00**	**4477959**	100	7.7
Water							
Low	18	16881	303858	5.00	151929	30.71283	2
Medium	126	16804	2117304	33.00	151236	30.57274	14
High	189	21279	4021731	62.00	191511	38.71443	21
Total			**6442893**	**100.00**	**494676**	100	13

Appendix 43: Estimation of the most productive state for growing AG across the Southern Nigeria

Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Ekiti							
Low	18	9281	167058	4.00	83529	15.99	2
Medium	41	3483	142803	3.00	31347	6.00	5
High	90	45295	4076550	93.00	407655	78.02	10
Total			**4386411**	**100.00**	**522531**	100.00	8
Lagos							
Low	18	19146	344628	18.00	172314	52.20	2
Medium	90	17535	1578150	82.00	157815	47.80	10
Total			**1922778**	**100.00**	**330129**	100.00	6
Ogun							
Low	18	36988	665784	5.11	332892	21.19	2
Medium	41	262	10742	0.08	2358	0.15	5
High	90	137343	12360870	94.81	1236087	78.66	10
Total			**13037396**	**100.00**	**1571337**	100.00	8
Ondo							
Low	18	22764	409752	3.26	204876	14.35	2
Medium	41	993	40713	0.32	8937	0.63	5
High	90	134865	12137850	96.42	1213785	85.02	10
Total			**12588315**	**100.00**	**1427598**	100.00	9
Osun							
Low	18	16302	293436	4.00	146718	15.98	2
Medium	41	4057	166337	2.00	36513	3.98	5
High	90	81686	7351740	94.00	735174	80.05	10
Total			**7811513**	**100.00**	**918405**	100.00	9
Oyo							
Low	18	115162	2072916	11.00	1036458	38.10	2
Medium	41	6978	286098	2.00	62802	2.31	5
High	90	180109	16209810	87.00	1620981	59.59	10
Total			**18568824**	**100.00**	**2720241**	100.00	7

Table 44: Estimation of the most productive state for growing EG across the Southern Nigeria.

Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Ekiti							
Low	64	9281	593984	4.30	83529	15.98546	7.11
Medium	177	1	177	0.001	9	0.001722	19.67
High	271	48777	13218567	95.70	438993	84.01282	30.11
Total			**13812728**	**100.00**	**522531**	100	26.43
Lagos							
Low	64	19146	1225344	20.00	172314	52.19596	7.11
High	271	17535	4751985	80.00	157815	47.80404	30.11
Total			**5977329**	**100.00**	**330129**	100	18.11
Ogun							
Low	64	36988	2367232	6.00	332892	21.18527	7.11
High	271	137605	37290955	94.00	1238445	78.81473	30.11
Total			**39658187**	**100.00**	**1571337**	100	25.24
Ondo							
Low	64	22764	1456896	4.00	204876	14.3511	7.11
High	271	135858	36817518	96.00	1222722	85.6489	30.11
Total			**38274414**	**100.00**	**1427598**	100	26.81
Osun							
Low	64	16302	1043328	4.30	146718	15.97531	7.11
Medium	177	7	1239	0.01	63	0.00686	19.67
High	271	85736	23234456	95.70	771624	84.01784	30.11
Total			**24279023**	**100.00**	**918405**	100	26.44
Oyo							
Low	64	115162	7370368	12.69	1036458	38.1017	7.11
Medium	177	78	13806	0.02	702	0.025807	19.67
High	271	187009	50679439	87.28	1683081	61.8725	30.11
Total			**58063613**	**100.00**	**2720241**	100	21.35

Table 45: Estimation of the most productive state for growing MG across the Southern Nigeria.

Productivity class	Yield (tonnes)	count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area (%)	Yield (tonnes/ha)
Ekiti							
Low	27	9284	250668	3.00	83556	15.99	3.0
Medium	162	48775	7901550	97.00	438975	84.01	18.0
Total			**8152218**	**100.00**	**522531**	100.00	15.6
Lagos							
Low	27	19139	516753	15.00	172251	52.21	3.0
Medium	162	17520	2838240	85.00	157680	47.79	18.0
Total			**3354993**	**100.00**	**329931**	100.00	10.2
Ogun							
Low	27	36991	998757	4.29	332919	21.19	3.0
Medium	162	137478	22271436	95.60	1237302	78.74	18.0
High	198	134	26532	0.11	1206	0.08	22.0
Total			**23296725**	**100.00**	**1571427**	100.00	14.8
Ondo							
Low	27	22774	614898	2.72	204966	14.36	3.0
Medium	162	135465	21945330	96.94	1219185	85.40	18.0
High	198	389	77022	0.34	3501	0.25	22.0
Total			**22637250**	**100.00**	**1427652**	100.00	15.9
Osun							
Low	27	16300	440100	3.07	146700	15.97	3.0
Medium	162	85720	13886640	96.91	771480	84.01	18.0
High	198	15	2970	0.02	135	0.01	22.0
Total			**14329710**	**100.00**	**918315**	100.00	15.6
Oyo							
Low	27	115162	3109374	9.00	1036458	38.10	3.0
Medium	162	187108	30311496	91.00	1683972	61.90	18.0
Total			**33420870**	**100.00**	**2720430**	100.00	12.3

Appendix 46: Estimation of the most productive state for growing SG across the Southern Nigeria

Ekiti							
Productivity class	Yield (tonnes)	Count (pixel)	Total yield (tonnes)	Yield (%)	Suitable area (ha)	Area %	Yield (tonnes/ha)
Low	18	9281	167058	2.00	83529	15.99	2.00
Medium	126	6926	872676	10.00	62334	11.93	14.00
High	189	41852	7910028	88.00	**376668**	72.09	21.00
Total			**8949762**	**100.00**	**522531**	100.00	17.13
Lagos							
Low	18	22764	409752	2.00	172314	52.20	2.38
Medium	126	16733	2108358	8.00	3321	1.01	634.86
High	189	119127	22515003	90.00	154494	46.80	145.73
Total			**25033113**	**100.00**	**330129**	100.00	75.83
Ogun							
Low	18	36988	665784	2.52	332892	21.19	2.00
Medium	126	3361	423486	1.60	30249	1.93	14.00
High	189	134244	25372116	95.88	1208196	76.89	21.00
Total			**26461386**	**100.00**	**1571337**	100.00	16.84
Ondo							
Low	18	22764	409752	2.00	204876	14.35	2.00
Medium	126	16733	2108358	8.00	150597	10.55	14.00
High	189	119127	22515003	90.00	1072143	75.10	21.00
Total			**25033113**	**100.00**	**1427616**	100.00	17.53
Osun							
Low	18	16302	293436	2.00	146718	15.98	2.00
Medium	126	5606	706356	4.00	50454	5.49	14.00
High	189	80137	15145893	94.00	721233	78.53	21.00
Total			**16145685**	**100.00**	**918405**	100.00	17.58
Oyo							
Low	18	115162	2072916	5.54	1036458	38.10	2.00
Medium	126	283	35658	0.10	2547	0.09	14.00
High	189	186804	35305956	94.36	1681236	61.80	21.00
Total			**37414530**	**100.00**	**2720241**	100.00	13.75

Appendix 47: Estimation of the total yield of crop productivity (tons) in the six geopolitical zones of Nigeria based on land areas

ZONE	AG	MG	SG	EG	Total yield
NWAG	104347348	1.88E+08	1.17E+08	2.68E+08	677951069
NEAG	138034725	3E+08	2.35E+08	3.22E+08	995419260
NCAG	130281211	2.54E+08	2.04E+08	3.9E+08	978929388
SWAG	58317199	89753666	61486272	1.8E+08	389628476
SSAG	54889831	1.13E+08	90780624	1.39E+08	397698680
SEAG	18781272	29672392	18781830	43139575	110375069

Appendix 48: Estimation of the most productive state for each of selected species; AG, MG, SG and EG across the Northern Nigeria based on land areas

State	Yield of AG (tonnes)	Yield of MG (tonnes)	Yield of SG (tonnes)	Yield of EG (tonnes)
Adamawa	12537939	33421433	28060164	24607440
Bauchi	22680709	57405472	47052540	42032349
Borno	40797521	96015128	90984006	61348284
Gombe	5625059	16360459	10989036	7131924
Taraba	30459572	84068810	69395040	47410515
Yobe	25933508	58628449	53969085	34574553

Appendix 49: Estimation of the most productive state for growing the selected bioenergy species; AG, EG, MG and SG in the South of Nigeria

State	**AG**	**EG**	**MG**	**SG**
Ekiti	4386411	13218744	16304436	8949762
Lagos	1922778	4751985	3354993	25033113
Ogun	13037396	37290955	23296725	26461386
Ondo	12588315	36817518	22637250	25033113
Osun	7811513	23235695	14329710	16145685
Oyo	18568824	50693245	30311496	37414530

Appendix 50: Python code for productivity analysis

Productivity.txt - C:\Users\Moses\Desktop\productivity_Py\Productivity.txt

File Edit Format Run Options Windows Help

```
#Moses issue

# Import system modules
import arcpy
from arcpy import env
from arcpy.sa import *

# Set environment settings
env.workspace = "C:\Users\Moses\Desktop\productivity_Py\Suitability_map"
arcpy.env.overwriteOutput = True

#workspace for intermidiate temporally files
TempoFolder = "C:\Users\Moses\Desktop\productivity_Py\temp"

# Set local variables
inRaster = Raster("adamamg.asc")

# Check out the ArcGIS Spatial Analyst extension license
arcpy.CheckOutExtension("Spatial")

# Execute Con
outCon = Con(inRaster == 0,27, Con(inRaster == 2,162,198))


# Save the outputs
outCon.save("C:\Users\Moses\Desktop\productivity_Py\Output\\adamamg.tif")

print "Done"
```

Appendix 51: Estimation of Cattle Stocking Density/ Carrying Capacity (CC) in Nigeria by Zone (Average 2011 -2013).

ZONE	Population	Suitable area (ha)	CC
AG			
NW	10067851	8,008,434	6
NE	5270614	11,483,529	6
NC	5527623	10,680,921	6
SE	15849	1,636,434	6
SS	152782	4,924,080	6
SW	139568	5,513,625	6
SG			
NW	10,067,851	8,155,404	6
NE	5,270,614	11,483,514	6
NC	5,527,623	10,680,930	6
SE	15,849	1,636,500	6
SS	152,782	4,924,080	6
SW	139,568	5,513,634	6
MG			
NW	10,067851	8,009,600	6
NE	5,270,614	11,483,500	6
NC	5,527,623	10,680,900	6
SE	15,849	1,636,400	6
SS	52,782	5,513,600	6
SW	139,568	5,513,600	6
EG			
NW	10,067,851	8,009,550	6
NE	5,270,614	11,133,846	6
NC	5,527,623	10,631,400	6
SE	15,849	1,636,353	6
SS	152,782	5,513,625	6
SW	139,568	5,513,625	6

Appendix 52: Estimation of Goat Stocking Density/ Carrying Capacity

(CC) in Nigeria by Zone (2011 -2013) on average

AG			
ZONE	Population	Suitable area (ha)	CC
NW	24111781	8008434	11
NE	8134410	11483529	11
NC	6716436	10680921	11
SE	4512678	1636434	11
SS	4772850	4924080	11
SW	10371584	5513625	11
SG			
NW	24111781	8155404	11
NE	8134410	11483514	11
NC	6716436	10680930	11
SE	4512678	1636500	11
SS	4772850	4924080	11
SW	10371584	5513634	11
MG			
NW	24111781	8009600	11
NE	8134410	11483500	11
NC	6716436	10680900	11
SE	4512678	1636400	11
SS	4772850	5513600	11
SW	10371584	5513600	11
EG			
NW	24111781	8009550	11
NE	8134410	11133846	11
NC	6716436	10631400	11
SE	4512678	1636353	11
SS	4772850	5513625	11
SW	10371584	5513625	11

Appendix 53: Estimation of Sheep Stocking Density/ Carrying Capacity (CC)

in Nigeria by Zone (2011 -2013) on average

AG			
ZONE	Population	Suitable area (ha)	CC
NW	23129581	45584389	11
NE	6603820	45584389	11
NC	5702809	42674151	11
SE	708978	6545687	11
SS	856966	20875385	11
SW	1524644	22054484	11
SG			
NW	23129581	8155404	11
NE	6603820	11483514	11
NC	5702809	10680930	11
SE	708977.6	1636500	11
SS	856966.2	4924080	11
SW	1524644	5513634	11
MG			
NW	23129581	8009600	11
NE	6603820	11483500	11
NC	5702809	10680900	11
SE	708977.6	1636400	11
SS	856966.2	5513600	11
SW	1524644	5513600	11
EG			
NW	23129581	8009550	11
NE	6603820	11133846	11
NC	5702809	10631400	11
SE	708977.6	1636353	11
SS	856966.2	5513625	11
SW	1524644	5513625	11

Appendix 54*:* Literature derived information for Switchgrass (Panicum virgatum L)

Author		Tittle	Year	Geographic scope	Information
Abdullahi et al.,		Effects of Fertilization and Irrigation on Establishment and Growth of Switchgrass (*Panicum virgatum* L.)	2013	Sokoto, Nigeria	The elevation of the study area was 242m, with mean annual rainfall between 552-600 mm. The average temperatures of 27-40ºC and minimum temperature of 18ºC was used.
Wang et al.,		A quantitative review comparing the yield of switchgrass in monocultures and mixtures in relation to climate and management factors.	2010	Illinois, USA	Crop survived at a base temperature of 10ºC, but higher biomass yield was obtained at optimum temperatures of 20-30ºC and annual precipitation of 400-1600mm. The optimum yield was achieved at 800mm with a total yield of 10.9tons/ha. Water availability (precipitation) was reported as a major factor for crop growth.
Sanderson et al.,		Switch grass as a Sustainable Bioenergy Crop.	1996	Texas USA	Yield varied with different temperature, rainfall and soil conditions in the study area. Seed dormancy was reduced at a minimum temperature of 4-10°C.
McLaughlin and Kszos		Development of switchgrass (*Panicum virgatum*) as a Bioenergy feedstock in the United States.	2005	Texas and North Dakota, USA	Water availability from May–July of the growing season was identified as the most important critical for achieving successful growth and yield. The crop is favoured by warmer soil temperatures, although high temperatures above 40ºC and soil pH less or equal to 4:0 or greater than 8.0 significantly reduced seedling survival. An average annual yield of 13.5t/ha was confirmed.

Kandel et al.,	Growth and Yield Responses of Switchgrass Ecotypes to Temperature	2013	Oklahoma, USA	Based on four different trial temperatures for the study; 15-23˚C, 20-28˚C, 25-33˚C, and 30-38˚C. It was reported that high temperatures reduced yield across all cultivars. The plant height was decreased at 38ºC for all cultivars while tiller number per plant increased at 30-38˚C. Node development rapidly decreased at 38˚C while leaf elongation rate was higher at moderate temperatures (33ºC). Crop development decreased at temperatures ≥ 38ºC. Temperature had significant effect on yield. Biomass of all cultivars rapidly decreased at 38˚C while highest yield was achieved at 20.3˚C. This study further stated that available water was a major factor for successful establishment.
Mitchell et al	Switchgrass	2014	Illinois, U.S.A	The optimum temperature for germination and growth was 20-30◦C, while germination was reduced at temperature < 20˚C.

Giannoulis et al.,	Cultivation cost and biomass productivity of Switchgrass (Alamo) in central Greece.	2009	West Thessaly plain, Greece	The daily maximum temperature of switchgrass fluctuates between 30-35ºC until the end of summer when the temperature stabilizes at 23-27ºC until mid-October. Also the minimum temperature fluctuates at 15-20ºC until the end of summer. During autumn, rainfall rapidly increases the growth of the crop. A total rainfall accumulation of 150mm was recorded between June and September. The production of switchgrass was limited due to insufficient available water, therefore irrigation was recommended. A total yield of 25 tons/ha was obtained.
Hashemi and Sadeghpour	Establishment and production of switchgrass grown for combustion: a review.	2013	Massachusetts, USA	The optimal temperatures for crop germination were 27-30°C. Although the species can emerge and grow at 20°C germination was reduced at temperatures < 20°C.
				Extreme soil pH levels affects switchgrass establishment. Therefore a pH level < 4.0 or > 8.0 amounts to a significant reduction in seedling survival.

Brummer et al.,	Switchgrass production in Iowa: economic analysis, soil suitability, and varietal performance.	2000	*Iowa*, USA	Switchgrass (both the Alamo and Cave-in-Rock) were established within the pH levels of 6.73 and 6.89. The aforementioned species were identified to favourably grow within soil organic matter contents of 2.41 and 2.31%.
Hanson and Johnson	Germination of switchgrass under various temperature and pH regimes	2005		The study reported that the optimal germination of switchgrass occurs relatively well with temperature range of 25-35 °C and a pH level of 5.0-8.0. The study indicated that switchgrass outside the above mentioned temperatures and pH levels would be unsuccessful.
Hartman et al.,	Potential ecological impacts of switchgrass biofuel cultivation in the Central Great Plains, USA.	2011	Central Great Plains, USA.	Switchgrass can adapt to a wide geographic and environmental locations. It can grow at monthly annual temperature of 25ºC, requires high water-use efficiency (mean annual precipitation of 300-1500 mm).
Rahman et al.,	Extension of energy crops on surplus agricultural lands: A potentially viable option in developing countries while fossil fuel reserves are diminishing	2014	Developing countries	Suitable altitudes, temperature and rainfall levels at 50-200m, 15-25ºC and 400mm are essential criteria for crop production.
Lewis et al.,	A fuzzy logic-based spatial suitability model for drought-tolerant switchgrass in the United States	2014	Great Plains (GP) region, USA	Switchgrass requires significant amount of water, while limited water supply could result in reduced yield.

[1]*Salon Paul* [2]*Salon and Miller*	Establishing Switchgrass for Biomass Production Guide to conservation plantings on critical areas for the Northeast	2012	USA. Northeast, USA	Management practices are not easily conducted on steep slopes > 35^o. Can tolerate a pH value of 5.5 and sufficient water availability. Yields 8.7 – 12.3 tons/ ha of dry matter. The choice of seeding method depends on slope level of the site. Grass drills cannot be used on steep slopes, although hydro seeding with wood fibre mulch can be used in steep slopes. Permanent irrigation was recommended for sites with little or no rainfall but too costly for growing a herbaceous energy crop. All warm season grasses including switchgrass grow efficiently from 18- 35°C, while a minimum temperature of 6°C is required. Requires high soil fertility, medium moisture, minimum and maximum pH level of 8 and 4.5, but prefers pH of 7. But can tolerate pH levels of 5.2 and 8.4.
Newman	Production of Biofuel Crops in Florida: Switchgrass	2008	Florida, USA	In South Florida, switchgrass (Miami) requires particularly higher organic matter content. Survived in soils ranging from sands to clay loams soils with pH levels of 4.5 to 7.6. The yield depends on site location In Florida, under average condition or without fertilizers about 4.5 to ~ 9tons/ ha was achieved. For a fertilized species with adequate available water, about 13.5tons/ha was obtained while best conditions resulted in 22tons/ha was obtained. About 22 tons/ha of Nitrogen was required in a low organic matter site. This implies that the crop requires a high organic matter content to survive.

Sanderson et al	Crop management of switchgrass	2012	Nebraska and South Central, USA	Conventional tillage was not possible for fields with steep slope due to the risk of soil erosion which leads to low yield. High water availability (frequent rainfall between 7-10 days) increased the chances of switchgrass survival. Successful establishment was determined by soil temperatures above 20ºC, while optimal seed germination and growth were found to be between 27 and 30ºC.
Nyoka et al.,	Management guide for biomass feedstock production from switchgrass in the Northern Great Plains	2007	Northern Great Plains-Dakota, USA	Temperature and water availability (soil moisture) are the two major factors for successful establishment of switchgrass. Switchgrass requires soil temperatures > 10ºC, while from 15–20ºC were ideal temperature ranges for optimal germination.
Wolf and Fiske	Planting and managing switchgrass for forage, wildlife, and conservation.	2009	Virginia, USA	Switchgrass establishment can be successful at 27- 30ºC and at soil pH level of >5, while adequate rainfall (water) is required for rapid germination of the species.

Arias et al.,	Classification of soil aptness to establish *Panicum virgatum* in Mississippi using sensitivity analysis and GIS	2009	Mississippi, USA	The growth and productivity of switchgrass is directly correlated with the level of water available (soil moisture) and amount of soil fertility (including soil pH and organic matter content). Although, the crop can tolerate pH values from 4.8 to 7, but pH values of 5.5 to 6 are required to achieve rapid growth and yield. Water holding capacity (available water) and organic carbon are the most important parameters for suitability.
Thapa, N.	Agro-climatic and land suitability mapping for switchgrass grown as a bioenergy crop in North Dakota	2012	North Dakota, USA	Limiting factors reported in this study are inadequate soil water availability (precipitation/ rainfall/ irrigation) and effect of temperature.
Hartman *et al.,*	Physiological and growth responses of switchgrass (*Panicum virgatum* L.) in native stands under passive air temperature manipulation.	2013	Kansas, USA	Soil had more influence on growth and yield than climate (temperature), although water availability was considered as a major factor for high productivity. Annual precipitation was 820 mm with approximately 75% of the rainfall received during the growing season (April–September). The mean daily air temperature in January weather is 1.2°C, while the temperature in July when the weather is warmest is 26 °C.

Wullschleger	Biomass Production in Switchgrass across the United States: Database Description and Determinants of Yield	2010	Southern USA	High temperature is a favourable factor for growth and yield. Higher yield was produced at an optimum annual temperature >10°C for upland cultivars and >15°C for lowland cultivars. The annual precipitation of the growing season was 300-1200mm, while higher yield occurred between 500-800mm. Sufficient water (precipitation) from April to September with a threshold value of ~ 600 mm had significant positive effect on biomass yield.
Fiorese & Guariso	GIS-based approach to evaluate biomass potential from energy crops at a regional scale	2010	Emilia-Romagna, Northern Italy	Unsuitable sites were identified as areas with elevation levels > 750 m; steep slopes > 20%; pH levels < 5.0 or > 8.5; average annual precipitation < 700 mm and average temperature < 10 ºC.
Parrish and Fike	The Biology and Agronomy of Switchgrass for Biofuels Agronomy of Switchgrass for Biofuels	2005	USA	The base temperature for switchgrass to germinate was 10◦C while the optimum temperature is at 35◦C. Higher yield was characterized by higher rainfall. Substantial yield of about 15 t/ ha per annum was produced in areas with sufficient rainfall and adequate soil fertility. Soil pH is not frequently a limiting factor for switchgrass establishment and could grow at a pH value of 3.7

Appendix 55*:* Literature derived information for Miscanthus *(Miscanthus giganteus)*

Author	**Tittle**	**Year**	**Geographic scope**	**Information**
Nixon and Bullard	Planting and growing Miscanthus, best practice guidelines.	2001	England, UK	Suitable soil pH levels between 5.5 and 7.5 were recorded. Plant growth was not possible below a threshold temperature of 6ºC. Yield varied between 12-20 t/ha for best climate.
Aylott et al.	Report Title: Domestic Energy Crops; Potential and Constraints Review	2012	England, UKs	Miscanthus requires about 40-100 mm of water in order to survive.
Williams and Douglas	Planting and managing giant miscanthus as a biomass energy crop,	2011	Washington DC, USA	In Europe, it was reported that plant increases at temperatures above 10ºC. Adequate rainfall was a major factor for achieving high biomass yield.
Caslin et al.,	Miscanthus best practice guidelines, Agriculture and Food Development Authority	2010	Northern Ireland	Productivity depends on water and temperature of the area. It was reported that it's impossible to record successful establishment of the crop below 15.5ºC. The crop requires high organic matter content and the optimal pH levels of 5.5-7.5. Water availability was considered as the major factor. High yield of about 10 -13 t/ha was obtained from the site.
Richter *et al.,*	Assessing on-farm productivity of Miscanthus crops by combining soil mapping, yield modelling.	2016	United Kingdom	Topography with slight slope <5% is suitable, 10% slope was above the threshold level (marginally suitable) while 15% was classified as unsuitable.

Widholm *et al.*,	Miscanthus: a promising biomass crop,	2010	Midwestern, USA	The growth of *Miscanthus giganteus* was reported to occur between 10 to 20ºC, while accumulated rainfall > 500mm was required for successful establishment.
Bowen & Hollinger	Model to determine suitability of a region for a large number of crops: Illinois State Water Survey	2004	Illinois, USA	Soil pH level of 6.5-8.0 classified as highly suitable, 8.0-8.3 moderately suitable, 8.3-8.5 marginally suitable and areas > 8.5 unsuitable. The climate was characterized by minimum and maximum temperature of 10-28 ºC and rainfall >300mm.
Lewandowski *et al*,	Miscanthus: European experience with a novel energy crop.	2000	Europe	Soil temperatures between 10 to 12˚C supported the growth of the crop during winter. About 30 t/ha of miscanthus (dry matter) was achieved at 15˚C in Southern Europe (Portugal). rapid growth was achieved at an average rainfall of 500-1000 mm and mean temperatures of 7.5 to 17:5 ˚C.

Appendix 56*:* Literature derived information for Alfalfa *(Medicago sativa)***.**

Author	**Tittle**	**Year**	**Geographic scope**	**Information**
Butler *et al.*,	Temperature Affects the Germination of Forage Legume Seeds.	2014	Southern Great Plains, USA	The study reported that alfalfa was not affected by temperature and about 96% germination of the crop occurred at temperature range of 10-35°C.
Undersander *et al.*,	Alfalfa management guide	2011	Northern, USA	Optimal growth of alfalfa in this region was a function of adequate pH values of 6.5-6.8. Although, slope was not considered as important for choosing a suitable site for alfalfa production, but level land (gentle slope) plays vital role for safety operation of machine during production.
FAO	Crop Information: Alfalfa	2018	California, USA	Alfalfa can adapt to diverse climate and soils, preferably a well-drained soil. The growth and establishment of alfalfa rapidly decreases at soil temperatures < l0°C and temperatures > 30°C. The optimal temperature for alfalfa growth is 25°C and the crop requires higher water uptake between 800 and 1600 mm per growing period.

Weaver *et al*.,	Alfalfa production in a grassland climate	1930	Nebraska, USA	It was also reported in this study that water (moisture or rainfall) is the preferred factor that leads to a successful establishment (growth) and yield of alfalfa.
Mueller and Teuber	Alfalfa Growth and Development, Irrigated Alfalfa Management for Mediterranean and Desert zones	2007	California, USA	In California, alfalfa survived at 18ºC, while optimal growth and development of the established crop was achieved between 20 to 24ºC. Alfalfa cannot survive at low or extremely high temperatures of 1.7ºC and 40ºC respectively.
Dixon and Kincheloe	Establishing a Successful alfalfa crop	2005	Montana, USA	Soil pH ranging from 6.5 to 7.0 is ideal for the establishment and growth of alfalfa, although higher pH can still be used.
Putnam *et al*.,	Alfalfa Production Systems in California.	2007	California, USA	The species was grown at a hot summer maximum temperature > 38ºC and cool winter of temperature of 16ºC. Rainfall accumulation > 8-18 inches (> 203-457mm) occurred during the growing seasons (from November to March). The region was also characterized by extremely hot summer temperature of 41ºC and warm winter season's temperature of 24ºC. The region was found to receive the highest allocation of irrigation water due to the low rainfall received. The essence of the irrigation practice was to enable adequate water supply to the crop.

				About 17% of alfalfa production was achieved across the region due to suitable soils ranging from sandy to other heavy soils like clay and silk. In California which is characterized by high elevation, freezing winter as well as warm summers has an average maximum and minimum temperature of 30ºC and -3ºC. The average rainfall recorded in the region was about 1,295mm per year. The High Desert Region of Los Angeles Basin is characterized by high elevation level of 1500 to 3000 feet (457 to 914 meters) and an accumulated annual rainfall of 127mm. Water is the most important parameter that can impact the growth and productivity of alfalfa.
Zhang *et al*.,	Yield Evaluation of Twenty-Eight Alfalfa Cultivars in Hebei Province of China	2014	Hebei Province, North China.	The elevation at the study area was 1480m. The mean temperature and rainfall of the area were 12°C and 600 mm respectively. The pH level of 8.0 was identified at 0-30 cm whereas the organic matter content was 8.61 g/ kg.
Chang *et al*.,	Alfalfa Carbon and Nitrogen Sequestration Patterns and Effects of Temperature and Precipitation in Three Agro-Pastoral Ecotones of Northern China	2012	North China	Water is the major factor limiting the plant while temperatures ≥ 10ºC is normally required for successful growth and development.

Orloff	Choosing appropriate sites for Alfalfa production	2007	California, USA	Alfalfa requires more water than any other factor (management practices) and insufficient water supply resulted in decreased yield. In the Central Valley of California about 1,220mm of water (irrigated) was required for growing alfalfa in each of the growing seasons. Soil pH values from 5.8 to 6.3 were highly suitable while pH values from 7.5 to 8.2 are marginally suitable. The pH values less than 5.8 or >8.2 were classified as unsuitable sites. Slope levels >12% were unsuitable, areas equal to 12% slightly suitable while gentle or near level areas were highly suitable site.
Haby *et al.*,	Alfalfa production on acid, humid-region soils.	1997	Coastal Plain of the Southern U.S.A	Adequate supply of water of about 508 mm and soil pH values from 6.8 to 7.0 were the critical factors for successful establishment and production of alfalfa in the Coastal Plain of the southern U.S.A. The crop was grown in October at 15.6ºC.
Yaghmaeian Mahabadi *et al.*,	Land Suitability Evaluation for Alfalfa and Barley Based on FAO and Fuzzy Multi-Criteria Approaches in Iranian Arid Region	2012	Arid Region, Iran	Mean annual rainfall of the study site was about 120 mm, while the mean annual temperature was 20.9 °C. Based on the climatic and soil requirements of the crop. Soil temperatures from 24-26, 20-24 and 26-28ºC were classified as highly suitable, 15-20 and 28-32ºC as moderately suitable, 10-15 and 32-40ºC were marginally suitable while areas with temperatures < 10 and > 40 were classified as not suitable. The relative humidity at 24-50 were highly suitable, 50-75 moderately suitable, 75-90 marginally suitable while < 20 or > 90 not suitable for alfalfa production. pH, 7.0-8.0 highly suitable, 8.0-8.2 moderately suitable, 8.2-8.5 marginally suitable and >8.5 not suitable.

Belal *et al*.,	Land Evaluation Based on GIS-Spatial Multi-Criteria Evaluation (SMCE) for Agricultural Development in Dry Wadi, Eastern Desert, Egypt	2015	Eastern Desert, Egypt	Suitable areas for alfalfa were characterized by slope levels between 0-2%, soil pH values between 7.6-7.3 and temperatures between 20-35°C.
Deng *et al*.,	GIS-based assessment of land suitability for alfalfa cultivation: a case study in the dry continental steppes of northern China	2014	Northern China	The soil pH values from 7.3-8.1 was classified as the most suitable areas for alfalfa growth. Suitable soil organic matter contents used were 0.18- 8.55%. The average annual rainfall 400-600 mm positively influenced the yield of alfalfa. The climatic conditions were reported to be also vital for the establishment and growth of alfalfa. The optimal mean temperatures between 15 to 20°C positively influenced the growth of the crop. The elevation levels of 2300m and slope levels < 15° were recommended in order to achieve a successful growth and harvesting of alfalfa in the region.
Xu *et al*.,	Identifying areas suitable for cultivation of *Medicago sativa* L. in a typical steppe of Inner Mongolia.	2016	Mongolia, China	This study identified temperatures at 25ºC and 35ºC as highly and highest acceptable (moderately) suitable temperatures for growing alfalfa in the region. The slope level 8.1 was deemed suitable for alfalfa cultivation.

Taati, *et al*.,	Agro-ecological zoning for cultivation of Alfalfa (*Medicago sativa* L.) using RS and GIS	2015	Qazvin province, Iran	Climate requirements were the major factors for determining suitable areas. The mean annual temperature of 14.1°C was suitable. The minimum and maximum altitudes considered for cultivation were 1141 m and 1488 m respectively. Soil fertility properties (soil pH, texture and organic material contents) were other limiting factors considered. Sufficient moisture (available water) was a preferred factor while a minimum temperature > 6.5 ºC recommended.
Jafarzadeh *et al*.,	Land suitability evaluation of Bilverdy Research Station for wheat, barley, alfalfa, maize and safflower.	2008	East Azarbaijan, Iran	The study identified that the most critical factors for determining land suitability for growing alfalfa were climate (including temperature and availability of water; rainfall and relative humidity). The area had average total rainfall of about 302.8 mm and mean temperature of 40ºC.
Li *et al*.,	Ridge-furrow planting of alfalfa (*Medicago sativa* L.) for improved rainwater harvest in rainfed semi-arid areas in Northwest China	2007	Northwestern, China	The annual mean maximum and minimum temperatures were 20.7 and 9.2ºC, respectively. Precipitation levels between 253-259.4mm was identified for cultivation of the species. The soil organic matter content of 0.8% at 0–20 cm for top soil was suitable for successful establishment of the crop.
Zhang *et al*.,	Yield Evaluation of Twenty-Eight Alfalfa Cultivars in Hebei Province of China. Journal of Integrative Agriculture	2014	Hebei province, China	The elevation of the study area was 1480 m, with a mean temperature of about 12°C and mean rainfall of about 600 mm were suitable for production. The pH level and organic matter contents were of 8.0 and 8.61 g/kg (0.861%) respectively while a high biomass yield of 62.75 t/ha was realized from the site.

Appendix 57: Literature derived information for Elephant grass (*Pennisetum Purpureum)*

Author	**Tittle**	**Year**	**Geographic scope**	**Information**
Singh *et al.*,	Elephant grass	2013	Georgia, USA	Rapid crop growth recorded at an optimum daily temperatures of 30–35°C which enabled high biomass yield of about 45 dry t/ha and approximately 80 dry t/ha per year. It was also found from the literature that low or no growth was recorded at temperature < 10°C. Elephant grass requires high annual rainfall ranging from 750-2500mm. A pH level ranging from highly acidic to alkaline with high organic matter content and elevation of <2100 m were also required.
Zhang *et al.*	Potential of four forage grasses in remediation of Cd and Zn contaminated soils.	2010	South China	A soil pH of 6.09; organic matter content of 3.92%; CEC of 79.7 mol/kg were the required characteristics suitable for growing elephant grass in the area.

Wang *et al*,	Biophysical properties and biomass production of elephant grass under saline conditions	2002	Brawley, California, USA	The study area was characterized by hot, dry summers with maximum temperature ≥ 38ºC and mild winter temperature of 23ºC. The low mean rainfall (60mm) gave room for irrigation in the area. Diverse soil types ranging from silty to clay were identified to support the growth of elephant grass.
Ferraris,	The effect of photoperiod and temperature on the first crop and ratoon growth of *Pennisetum purpureum* Schum	1978	Queensland, Australia.	Elephant grass was successfully grown at maximum temperature between 30-25ºC and minimum temperature of 21-16ºC. It was discovered that the higher the temperature the more yield potential while higher leaf was achieved in this site at 30-25ºC. It was reported that low temperature reduces the growth, hence the greatest limitation to successful establishment of the crop. It was also reported that the productivity of elephant grass was limited by temperature.
Erikson *et al*,	Water Use and Water-Use Efficiency of Three Perennial Bioenergy Grass Crops in Florida	2012	Florida, USA	About 850 to 1150 mm of water was used during the growing season for cultivation of elephant grass with biomass yields of 35- 40 t/ha achieved. Irrigation plays an important role in areas with insufficient rainfall. The study further reported that annual rainfall of about 1228 mm and average daily air temperature of 27.2 °C and 12.4 °C were received around Gainesville in Florida between July and January respectively.

Obok *et al*,	Forage potentials of interspecific hybrids between elephant grass selections and cultivated pearl millet genotypes of Nigerian origin	2012	Calabar, Nigerian	A pH value of 6.6, high organic matter content of 14.9 g/kg, and exchangeable calcium 3.53 cmol/kg were required. The mean minimum and maximum temperatures ranged from 14.3 to 26.8°C (between Novembers to May). The relative humidity of the study area was very high ranging from 85- 90% through May, August to early November of 2010 respectively.
Ohimain *et al*,	Bioenergy Potentials of Elephant Grass, *Pennisetum purpureum*	2014	Bayelsa State, Nigeria.	The study recorded pH values of 5.6–6.0.
Pratumwan *et al.*	GIS-Based Assessment of Napier Grass Potential for Electricity Generation in Thailand:	2015	Thailand	Elephant grass grows in diverse soil types and climates with soil pH of 4.5-8.0, average annual rainfall > 1,000 mm
Ayotamuno *et al.*,	Comparison of corn and elephant grass in the phytoremediation of a petroleum hydrocarbon-contaminated agricultural soil in Port Harcourt, Nigeria	2006	Port Harcourt, Nigeria	The average annual rainfall of the area of study was 2700mm with an average temperature of 27^{o}C.
Ansah *et al*.,	Herbage yield and chemical composition of four varieties of Nappier (*Pennisetum Purpureum*) grass harvested at three different days after planting	2010	Kumasi, Ghana	The average annual rainfall was 1194 mm, while the mean maximum and minimum temperatures of 34^{o}C and 27^{o}C. High dry matter yield of 85.4tons/ha without fertilizers and about 130tons/ha obtained with the application of 1320kg/ha of nitrogen fertilizer.

Appendix 58: Accumulated annual rainfall (millimetre; mm) by the six geopolitical zones of Nigeria distribution by the 6 geopolitical zones of Nigeria

Zone	Mean Rainfall
North Central	1772.18
North East	1764.24
North West	1362.12
South East	2041.29
South South	2240.82
South West	1824.73

Appendix 59: Monthly 6-year mean (2008-2013) rainfall (mm) across the NC Geopolitical zone

Month	Mean Rainfall
Jan	22.62
February	34.07
March	52.62
April	157.76
May	159.32
June	259.74
July	271.19
August	295.45
September	271.58
October	258.78
November	48.02
December	90.03

Appendix 60: Monthly 6-year mean (2008-2013) rainfall (mm) across the NE Geopolitical zone

Month	Mean Rainfall
Jan	22.37
February	33.51
March	43.24
April	141.1
May	158.63
June	259.11
July	251.22
August	294.26
September	267.36
October	258.57
November	47.27
December	8.98

Appendix 61: Monthly 6-year mean (2008-2013) rainfall (mm) across the NW Geopolitical zone

Month	Mean Rainfall
Jan	4.43
February	8.45
March	20.5
April	81.51
May	104.19
June	199.43
July	276.67
August	305.48
September	252.41
October	258.58
November	17.3
December	2.74

Appendix 62: Monthly 6-year mean (2008-2013) rainfall (mm) across the SE Geopolitical zone

Month	Mean Rainfall
Jan	27.07
February	61.4
March	64.7
April	170.25
May	181.42
June	279.22
July	384.29
August	319.6
September	292.62
October	275.73
November	75.54
December	11.13

Appendix 63: Monthly 6-year mean (2008-2013) rainfall (mm) across the SS Geopolitical zone

Month	Mean Rainfall
Jan	30.19
February	70.02
March	70.69
April	183.97
May	189.91
June	305.68
July	422.97
August	334.45
September	297.59
October	296.22
November	81.05
December	17.19

Appendix 64: Monthly 6-year mean (2008-2013) rainfall (mm) across the SW Geopolitical zone

Month	Mean Rainfall
Jan	17.89
February	38.67
March	65.89
April	166.14
May	158.78
June	275.5
July	296.12
August	238.13
September	285.54
October	236.48
November	58.86
December	12.79

Appendix 65: Sensitivity analysis (SA) of the estimated biomass productivity in the six geopolitical zones of Nigeria

Specie	Zone	Productivity class	Yield (tons/ha)	20%_increase	20%_decrease	No of count (pixel)	20%_yield_increase	20%_yield	Original-yield
AG	SW	Medium	4.5	5.4	2.1	15773	766568	298110	646693
	SS	Medium	4.5	5.4	2.1	7553	367076	142752	309673
	NW	Medium	4.5	5.4	2.1	43124	2095826	815044	1768084
	NE	Medium	4.5	5.4	2.1	177195	8611677	3348986	7264995
	NC	Medium	4.5	5.4	2.1	10577	514042	199905	433657
MG	SW	Medium	18	21.6	14.4	612086	118989518	79326346	99157932
	SS	Medium	18	21.6	14.4	494580	96146352	64097568	80121960
	SE	Medium	18	21.6	14.4	29997	5831417	3887611	4859514
	NW	Medium	18	21.6	14.4	770023	149692471	99794981	124743726
	NE	Medium	18	21.6	14.4	300	58320	38880	48600
	NC	Medium	18	21.6	14.4	458777	89186249	59457499	74321874
SG	SW	Medium	14	16.8	11.2	33278	5031634	3354422	4193028
	SS	Medium	14	16.8	11.2	6	907	605	756
	SE	Medium	14	16.8	11.2	493343	74593462	49728974	62161218
	NW	Medium	14	16.8	11.2	773451	116945791	77963861	97454826
	NE	Medium	14	16.8	11.2	1174188	177537226	118358150	147947688
	NC	Medium	14	16.8	11.2	875855	132429276	88286184	110357730
EG	SW	Medium	19.7	23.64	15.76	86	18297	12198	15222
	SS	Medium	19.7	23.64	15.76	308959	65734117	43822745	54685743
	SE	Medium	19.7	23.64	15.76	156656	33330131	22220087	27728112
	NW	Medium	19.7	23.64	15.76	708583	150758119	100505413	125419191
	NE	Medium	19.7	23.64	15.76	1065499	226695567	151130378	188593323
	NC	Medium	19.7	23.64	15.76	160057	34053727	22702485	28330089

Appendix 66: Sensitivty analysis of the estimated cellulosic ethanol yield (billion litres) in each of the six geopolitical zone

Specie	ZONE	Yield (000 tonne)	20%_increase of glucose composition (%)	20%_decrease of glucose composition (%)	20%_increase_ethanol	20%_decrease_ethanol	Ethanol_Original
AG	NW	104347	0.75	0.50	38.65	25.77	31.95049753
	NE	138035	0.75	0.50	51.13	34.08	42.26535916
	NC	130281	0.75	0.50	48.26	32.17	39.89128224
	SW	58317	0.75	0.50	21.60	14.40	17.85635724
	SS	54890	0.75	0.50	20.33	13.55	16.80691885
	SE	18781	0.75	0.50	6.96	4.64	5.750706618
MG	NW	188000	0.59	0.39	54.78	36.21	45.49445316
	NE	300000	0.59	0.39	87.41	57.78	72.59753165
	NC	254000	0.59	0.39	74.01	48.92	61.46591013
	SW	89754	0.59	0.39	26.15	17.29	21.71964869
	SS	113000	0.59	0.39	32.93	21.76	27.34507025
	SE	29672	0.59	0.39	8.65	5.72	7.180474724
SG	NW	117000	0.50	0.33	28.89	19.07	23.69050063
	NE	235000	0.50	0.33	58.03	38.30	47.58348418
	NC	187514	0.50	0.33	46.30	30.56	37.96838065
	SW	61486	0.50	0.33	15.18	10.02	12.44991937
	SS	90781	0.50	0.33	22.42	14.79	18.38152505
	SE	18782	0.50	0.33	4.64	3.06	3.80299962
EG	NW	268000	0.61	0.40	80.74	52.94	67.50088861
	NE	322000	0.61	0.40	97.00	63.61	81.10181392
	NC	390000	0.61	0.40	117.49	77.04	98.22890506
	SW	180000	0.61	0.40	54.23	35.56	45.33641772
	SS	139000	0.61	0.40	41.87	27.46	35.00978924
	SE	43140	0.61	0.40	13.00	8.52	10.86552107

Appendix 67: Increase in glucose composition of selected bioenergy crops at ±20% to enable a sensitivity analysis on cellulosic ethanol production in Nigeria

Component	Glucose 1	Glucose 2	Average (estimated)	20%_increase	20%_decrease
Switchgrass	38.8	43.7	41.3	49.56	33.04
Miscanthus x giganteus	48.4	49.5	49	58.8	39.2
Elephant grass	57.8	50.3	50.6	60.8	40.4
Alfalfa	67.5	57	62.3	74.8	49.8