EVALUATION OF *PROSOPIS JULIFLORA* PRODUCTIVITY FOR CARBON STOCKS AND ANIMAL FEEDS IN SELECTED DRYLAND SITES, MAGADI SUBCOUNTY, KENYA

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DECLARATION

This thesis is my original work and has not been presented before for award of a degree in any other University.

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DEDICATION

I dedicate this work to my aging father, Mr. Bernard Kyuma Kavila, a stickler for hard work and whose open love for education has earned him the nickname “musomu”, meaning the educated, even though the furthest he went in his educational exploits was the former and colonial standard eight level. His passion for education has equally earned our rural location a nickname “Kwa musomu” meaning the place of the educated people.

At an early age he introduced me to the habit of hard work exemplified by the many hours my siblings and I would put in the family farm every time schools closed for the holidays. These efforts were to ensure the family was food secure. We achieved this goal over the years and it engrained in me the culture of hard work which endures in me to date. This culture was manifested no better than during this academic journey which was fraught with many challenges including balancing my employment requirements, my family obligations, my social desires and my academic exploits. The many days I would spend in the bush supervising data collection, the many visits to my supervisors’ offices in search of academic guidance, the many visits I undertook to various organizations looking for data and advice, underpinned my desire and determination to complete the journey I voluntarily and consciously undertook in 2012. This effort was compounded by a road accident I was involved in, which would keep me admitted in hospital for two weeks and introduce me to the world of disabled people and the attendant challenges.

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LIST OF ACRONYMS

AGB	Above ground biomass
ANOVA	Analysis of variance
APAR	Absorbed Photo-synthetically Active Radiation
ASAL	Arid and semi-arid lands
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CBD	Convention on Biological Diversity
CBS	Central bureau of statistics
CO_2	Carbon Dioxide
DEM	Digital elevation model
D30	Basal diameter at 30 meters above ground
DBH	Diameter at breast height
DRSRS	Department of resource survey and remote sensing
ETM+	Enhanced Thematic Mapper
FAO	Food and agriculture organization of the United Nations
GLM	General linear model
GoK/ PDNA	Government of Kenya - Post-Disaster Needs Assessment
GHG	Greenhouse gases
GIS	Geographical information systems

ILRI	International livestock research institute
IPAR	Intercepted Photosynthetically Active Radiation
H	Height
IBLI	Index based livestock insurance
ICRAF	International center for research in agroforestry
IPCC	Intergovernmental Panel on Climate Change
KLIP	Kenya livestock insurance programme
KNBS	Kenya national bureau of statistics
Landsat	Land imagery Satellite run by NASA
LUE	Light Use Efficiency factor
MODIS	Moderate-resolution Imaging Spectroradiometer
MSS	Multispectral Scanner
NASA	National Aeronautics and Space Administration
NDMA	National drought management authority
NDVI	Normalized Difference Vegetation Index
NIR	Near infra-red
NPP	Net primary productivity
PAR	Photosynthetically Active Radiation
SPOT	Satellite system, run by Spot Image, France

TM	Thematic Mapper
UNEP	United Nations Environmental Programme
WISP	World initiative for sustainable pastoralism

ABSTRACT

Factors affecting *Prosopis juliflora* productivity and its spread patterns on the hillslopes and floodplain landscapes were evaluated in the drylands of Magadi subcounty, Kenya. The above-ground biomass and carbon stocks were estimated using allometric equations based on several tree dimensions. The productivity of *Prosopis* pods was assessed over a period of ten months from a random sample of 320 *Prosopis* trees on the floodplains and hillslopes landscapes. Time series trends for prosopis biomass, monthly rainfall, temperatures; cattle, sheep and goats populations were analyzed from 2000 to 2014. MODIS NDVI and NPP (250m) data was used to determine *P. juliflora* biomass and its temporal spread dynamics. Four categories of eight plots measuring 900m^2 each were randomly selected, and fenced off into dense, dense managed, moderate and sparse densities respectively. The managed dense plots had the *Prosopis* trees pruned and spaced at five meters apart. Of the 320 *Prosopis* trees, 128 were randomly selected for destructive sampling for fresh weights determination for the development of *Prosopis* biomass estimation models. The mean monthly temperatures increased from 33^{0}C in 2000 to 37^{0}C in 2014; rainfall decreased from 600mm in 2000 to 250mm in 2014 and the divergence from the long term mean rainfall (450mm) decreased from 585mm to 403mm. At the same time cattle population decreased while sheep and goats populations remained stable. *P. juliflora* spread correlated positively ($r=0.2$; $P<0.05$) with mean monthly temperature and negatively ($r=-0.4$; $P<0.05$) with rainfall and other vegetation cover in floodplains but not in the hillslopes parts of the study area. It also correlated negatively with cattle populations ($r=-0.4$; $P<0.05$). In 2008, herbaceous cover, shrublands, and open trees together with bare areas constituted 50%, 30% and 22% respectively, out of which 70% had been replaced by *Prosopis* by 2014. The *Prosopis* NDVI in the floodplain had a lower mean (0.49) while on the hillslopes it was 0.78. The annual rate of *Prosopis* spread was 0.13 km^2, 4.76 km^2 and 13.09 km^2 respectively in the floodplains, while in the hillslopes, the rate of spread was less (5.36 km^2, 5.37 km^2 and 5.29 km^2) in 2000, 2006 and 2013. The basal diameter was the most important dimension among among diameter at breast height, crown width and tree heights in estimating. The dense managed category in the hillslopes held the highest *Prosopis* biomass (44.13 tons/ha) followed by dense unmanaged category (43.68 tons/ha). The dense unmanaged category of the floodplains had lower estimates (34.15tons/ha) followed by dense managed category (28.01 tons/ha). The moderately and sparsely dense categories in both landscapes recorded the lowest *Prosopis* biomass estimates (18.75 and 3.47tons/ha in hillslopes and 12.72 and 5.09tons/ha in floodplains). *Prosopis* biomass increased in the dense *Prosopis* clusters in hillslopes landscape, but there was no biomass change in the moderate and sparse density clusters. Management increased pod production in the hillslopes landscape. *Prosopis* pods were produced throughout the year, but peaked in the middle of the rain season. There are viable *Prosopis* biomass and pod quantities in the dense managed hillslopes landscape to sustain *Prosopis* based trade in carbon stocks and animal feeds production.

Keywords: Carbon, climate, feeds, livestock, *P. juliflora,* pods, productivity

1. CHAPTER 1: INTRODUCTION

1.1. Background

Native to Latin Americas, *Prosopis juliflora* (Sw.) DC, a plant of the *Leguminoceae* family (Silva, 1986), and also known as *algarroba, mesquite* and *Mathenge* in Kenya (Andersson, 2005), was introduced for land rehabilitation in Tana River County, (Choge and Pasiecznik, 2006), in the 1970's and 1980's (Wahome *et al.*, 2008). Due to its superior adaptation characteristics to climate variability, tolerance to aridity and massive seed production, *Prosopis* is taking over grazing and farm lands (Tewari *et al.,* 2000; Pasiecznik *et al.,* 2001). It is estimated that one tree can produce up to 80 kg of pods in one season. It is also estimated that 2% of Kenya's landmass in now under *Prosopis*; and its pod production potential has been estimated to be 60,000 tonnes per year in Kenya though these statistics require scientific verification. If *Prosopis* stands were managed in terms of spacing and pruning, an estimated 200,000 tonnes of pod yields per year, could be realised.

The arid and semi arid lands (ASAL) communities complain about this new and difficult to eradicate plant that is of little benefit (Choge *et al.,* 2006; Wahome *et al.,* 2008). However, so far the USA, Australia, South Africa and Sudan, among other countries have tried and failed to eradicate it. Among other options is to find an economic use for its products to enable the inhabitants of the *Prosopis* invested areas benefit and control its spread (Pasiecznik *et al.,* 2001). *Prosopis* and its products (pods and biomass) have been used successfully and profitably for timber, human food, animal feed in several countries of the world including Brazil, Argentina, Peru, Chile and India.

Research has shown that *Prosopis* pods' nutrient composition is similar to the brans and could supplement them in the 400,000 tons of maize and wheat bran used in animal feed rations in

Kenya (Wahome *et al.,* 2008; Pasiecznik *et al.,* 2001). This would help control feed prices and reduce importation (Githinji *et al.,* 2009). The levels of nutrients from literature show a reasonable feed resource, especially for Kenya, which has a narrow feed base. In terms of the primary nutrients (energy and protein), the pod flour is a useful feedstuff. The digestibility of the feedstuff is comparable to others of similar composition and therefore may serve as an alternative.

1.2. Problem statement

Climate variability and population increase in the pastoral areas have contributed to the degradation of grazing lands. This degradation has led to changes in vegetation cover and *Prosopis* is taking over the grazing lands. Once introduced, *Prosopis juliflora* is hard to eradicate and its rapid spread is aided by climate variability. As a result, livestock production is declining. Spread of the plant can be limited if it's rich seed bearing pods were to find a commercial use thus removing them from the environment. In addition, communities in invaded areas would derive additional benefits if they could trade in carbon credits from it. However, the relevant information to the development of *Prosopis* pod based animal feed business and trading in *Prosopis* carbon credits is lacking. This study generated information that will contribute to the knowledge of predicting future spread patterns of *Prosopis*, as well as determining relationships between *Prosopis* spread with climate variations, other vegetation and livestock populations. *Prosopis* biomass and carbon stocks were also estimated and will assist in establishing the foundations for trading in its carbon credits and use of *Prosopis* pods in animal feeds production. Armed with this information, the affected communities can lay strategies to improve animal productivity, enhance incomes and build their resilience to climate variability.

1.3. Justification

Prosopis juliflora has been used for combating land degradation, providing high quality hard wood timber, animal feed ingredients and human food (Pasiecznik, *et al.,* 2001). Despite the well documented properties of *Prosopis* pods as animal feed ingredients (Mathur and Bohra, 1993), there is no observed uptake by the pastoral communities and the animal feed manufactures in Kenya. Reasons advanced include lack of knowledge on its composition, lack of information on the productivity of the *Prosopis* plant and the lack of consistency and reliability in the supply of the *Prosopis* pods flour to the feeds factories. Production of *Prosopis* pods and biomass has not been well documented in Government and research institutions; and the entrepreneurs lack reliable source of information on *Prosopis (*Pasiecznik, *et al.*, 2001; Wahome *et al.,* 2008; Choge and Pasiecznik, 2006).

Economic feasibility studies on *Prosopis* pods and biomass have not been adequately addressed (Wahome *et al.,* 2008), and thus feed manufacturers lack interest for this potentially important ingredient for animal feeds. In 2009, the animal feeds industry in Kenya used 350,000 tons of maize and wheat bran, out of which 8% was imported and the demand was 400,000 tons (Githinji *et al.,* 2009). Drought intervention is one of the leading consumers of animal feeds produced in Kenya (GoK - PDNA, 2012). *Prosopis* is now found in 18 dryland Counties of Kenya whose major livelihood is livestock keeping.

Given its adaptation to moisture stress, high temperatures and degraded soils in the drylands, *P. juliflora* provides an opportunity for carbon sequestration to benefit the pastoralists from carbon trade–off schemes and also presents an option for alternative source of protein-rich and high energy animal feed and income to pastoral households. The determination of species capacity to store carbon and the method used is a prerequisite for a Carbon credit trade project (Tennigkeit and Wilkes, 2008). Similarly, *Prosopis* pods utilization for animal feeds and its commercialization requires in-depth understanding of its productivity as a prerequisite for sustainable use.

This study was therefore carried out to provide ecological and socio-economic empirical data to inform exploitation opportunities presented by *Prosopis juliflora*. This was achieved by determining its capacity to store carbon for carbon trade and its ability to provide pods for sustainable production of alternative animal feeds. Three challenges of the 21st century namely, the impacts of climate change, shortage of animal feeds and impoverishment caused by lost livelihoods was addressed, with the ultimate goal of improving livestock productivity and household incomes for enhanced pastoral resilience against climate variability.

1.4. Research gaps

Information on relationships between climate variability, human and livestock population and vegetation trends was an important knowledge gap (Galvin *et al.*, 2004; IPCC 2007). There were also knowledge gaps relating Prosopis biomass with carbon stock estimates and pod yield estimates (Singh G. and Bilas Singh, 2011; Tewari *et al.*, 2000; Tennigkeit and Wilkes, 2008). Although a lot of studies have been done on the climate variability (WISP, 2004; Galvin *et al.*, 2004; IPCC 2007; Resilience Alliance, 2010; Tennigkeit and Wilkes, 2008; WISP, 2007) the relationships between the climate variables, livestock population trends and the other vegetation dynamics were inadequately explained. (Although the *Prosopis* pods are documented as good sources of alternative animal feed ingredients for a variety of livestock (Wahome *et al.*, 2008; Pasiecznik *et al.*, 2001), the quantities that could be harvested was yet to be determined.

1.5. Overall Objective

The overall objective was to evaluate the effects of climate variability on the spread of *Prosopis juliflora* and its relationship with the other plants species and livestock populations; its biomass potential for carbon storage and the potential for pods production that may be useful as animal feed in the pastoral drylands of Magadi, Kenya**.**

1.6. Specific Objectives

The following are the specific objectives:

i. To determine the temporal relationship between climate variables (rainfall and temperature), vegetation cover dynamics and *P. juliflora* colonization and livestock populations dynamics

ii. To determine the above ground biomass production and carbon stocks to model potential for trading in carbon credits from *P. juliflora*

iii. To examine the seasonal pods production in the managed and unmanaged *Prosopis* stands to demonstrate amounts potentially available for use as animal feed.

1.7. Hypothesis

The following are the hypotheses:

i. There is no relationship between climate variables (rainfall and temperature), vegetation cover dynamics and *P. juliflora* colonization and livestock population’s dynamics over time

ii. The above ground biomass and carbon stocks cannot be used to model potential for trading in carbon credits from *P. juliflora*

iii. There is no seasonality in quantities and quality of *Prosopis* pods potentially available for use as animal feed.

2. CHAPTER 2: LITERATURE REVIEW

2.1. *Prosopis* and its global distribution

Prosopis trees belong to the family *Leguminoceae*, subfamily *Mimosoideae*, genus *Prosopis*. The genus contains about 45 species, some of which are *Prosopis juliflora*, *Prosopis pallida*, *Prosopis alba, Prosopis chilensis, Prosopis kuntzei*, *Prosopis nigra*, *Prosopis glandule,* among others (Silva, 1986; Choge and Pasiecznik, 2006.)

Prosopis is believed to have originated from the South and Central American countries such as Argentina, Peru, Bolivia, Colombia, Chile, Paraguay, Mexico, Uruguay, Costa Rica, Mexico and Venezuela. It is also native to the southern parts of USA, (Silva, 1986). It has been widely introduced throughout the world over the last 200 years by travelers, explorers, missionaries, administrators and researchers (Tewari, *et al.*, 2000). It is now found in many countries including Australia, Bahamas, Brazil, Cambodia, Cuba, Dominican Republic, Haiti, India, Indonesia, Iran, Jamaica, Kenya, Malaysia, Myanmar, Pakistan, Philippines, Senegal, South Africa, Sri Lanka, St Lucia, Sudan, Tanzania, Thailand, Trinidad and Tobago, Uganda, and Vietnam (Pasiecznik. *et al.*, 2001). The first records of *Prosopis* introduction to Africa date back to 1820s when they were introduced to Senegal, 1890s in South Africa, 1917 in Sudan and 1948 in Kenya (Choge and Pasiecznik, 2006)

2.2. *Prosopis juliflora* (Sw.) DC.

Prosopis juliflora is an evergreen tree with a large crown and an open canopy, growing to a height of 5-10 m. The stem is green-brown, with thorns and the bark is rough and dull red. The root system includes a deep taproot and lateral spreading roots. Leaves are compounded and the flowers are lateral to the axis with a tubular, light greenish-yellow calyx with hooded teeth, composed of petals. The fruit is a pod, with a mesocarp and seeds with an endosperm surrounding the embryo and cotyledons (ICRAF, 1992)

It is a very hardy and versatile tree with the ability to grow where virtually no other trees can survive such as dry degraded grasslands and wastelands with scanty and erratic rainfall, shifting sand dunes, eroded hills and river beds and saline terrains (Yoda, 2012; Silva, 1986). It is fast growing and reproduces mainly through seeds dispersed through the droppings of livestock and wildlife (ICRAF, 1992). Areas suitable for *Prosopis* growth are within the altitudes of 0-1500 m, mean annual temperatures of 14-34^{0}C and mean annual rainfall of 50-1200 mm. It can grow on a variety of soils including rocky hills, saline flats, on shifting sand dunes and coastal sand, although it attains its best size in localities protected from wind and having the water table not far below the surface. It can grow in waterlogged conditions and is tolerant to high salinity (Silva, 1986).

2.3. Prosopis in Kenya

Prosopis juliflora was introduced in Kenya in the 1970's and 1980's to rehabilitate degraded lands and combat desertification. It rapidly spread and became an invasive species that now occupies an estimated 6,000 square km in 18 Counties, colonizing about 2% of the country's land mass. Commonly known as *'Mathenge'*, *Prosopis juliflora* is a thorny, often multi-branched evergreen tree found mainly in arid and semi-arid areas of Kenya (Choge and Pasiecznik, 2006). It grows well in regions with 100 to 600 mm rainfall. It is a medium to a tall tree on maturity (3 to 15 metres) and sometimes shrubby, depending on soil type and climate (Tewari *et al.,* 2000). They mostly occur in high densities within moist areas (wetlands) forming an evergreen vegetation cover even in dry season and thriving very well when most other plants have dried up or have shed their leaves (Koech *et al.,*2010). It is a leguminous plant with the ability to improve soil fertility by fixing atmospheric nitrogen and through biomass decomposition (Bekele-Tesemma *et al.,* 1993)

2.4. ***Prosopis*** **use, control and itsrelationship of with pastoral livestock production**

Prosopis juliflora has become invasive in several countries where it was introduced (Pasiecznik *et al.,* 2001). It is difficult and expensive to remove once established as it can regenerate from the stem stumps, the many seeds and roots (Tewari *et al.,* 2000). It forms impenetrable thickets which prevent animals and humans from accessing feed, food and watering resources. It takes over pastoral grasslands and competes for the scarce water. In the Kenyan pastoral lands, *Prosopis* aggressive growth has led to a monoculture, denying native and palatable plants water and sunlight, and therefore depriving feed for pastoral animals (Koech *et al.,* 2010; Davies and Nori, 2008).

The government with stakeholders have been looking for ways to utilize the tree's products (wood, fruits, leaves and biomass) but the pastoralists who call it the "devil tree" insist that P. *juliflora* be eradicated (Koech *et al.,*2010). The powerful adaptive and aggressive abilities of *P. juliflora,* thriving in almost all types of soil and in varying climatic conditions has easily out-done most native competitors (Silva, 1986). Furthermore, the high number of viable seeds that germinate and grow very fast when in contact with moisture is the cause of the high densities of invasions that out-compete and subjugate other plant species with relative ease (Fagg and Stewart, 1994). Its success in terms of fast growth and adaptability to arid areas is the cause of invasiveness and reduction of agricultural productivity and biodiversity (Fagg and Stewart, 1994; Pasiecznik *et al.,* 2001).

Eradication programmes using manual, mechanical and chemical methods have given limited success. Some of these methods are effective for a short time, but *Prosopis* generally returns

(Wahome, *et al.,* 2008). This is due to the re-growth from stumps and massive numbers of seeds stored in the ground (Hong *et al.,* 1996). Seeds usually lie dormant in the soil for many years and germination is stimulated by soil disturbance and sudden moisture build-up (Albrecht, 1993; Bekele-Tesemma *et al.*, 1993). There is no geographical region in the world where *Prosopis* species have been permanently eliminated after being introduced (Choge and Pasiecznik, 2006). Global consensus now advocates for its control through utilization. The use of wood and pods will slow its aggressive growth and take advantage of its adaptation to adverse environments (Pasiecznik *et al.,* 2004).

The *Prosopis* plant has been used in various ways. *Prosopis juliflora* pods are valuable sources of carbohydrates, sugars and proteins for both livestock (Table 2.1) and human populations (Mathur and Bohra, 1993; Primo *et al.*, 1986; Silva, 1986).

Table 2.1: Nutritional content of *Prosopis* juliflora pods

Nutrient of Interest	Low	average	High
Dry matter, %	77.8	86.6	92.6
Energy, MJ/kg	7.9	9.9	10.8
Crude protein, %	7.1	11.7	21.8
Crude fiber, %	10.9	20.1	32.2
Nitrogen free extract, %	29.7	58.6	75.2
Dry matter Digestibility, %	38	46.5	55

Source: Wahome *et al.,* (2008); Pasiecznik *et al.,* (2001)

The pods flour may make up 40-60% of dairy concentrate rations. It is also fed to goats and sheep, pigs and poultry (Koech *et al.,* 2010; Tewari, 2011**;** Primo *et al.,* 1986). Ripe pods contain an average of 12-14% crude protein. It has been fed unmixed to cattle, goats and sheep to maintain their body conditions and survive feed scarcity periods (Pasiecznik *et al.,* 2004), for example, drought. P. *juliflora* pod flour have used in preparing human food, including bread, sweets, syrup and coffee (Tewari, 2011).

Prosopis juliflora has also been used in apiculture. It is a major honey source in Bolivia, Jamaica, Pakistan, Western Australia and elsewhere due to its very copious nectar flow (Harsh, 2011). The stems and branches are used as fuel. They make good firewood and provide excellent charcoal (Harsh 2011). *Prosopis* biomass has been used for power production (Kumar *et al.*, 2011). There is a large potential for P. *juliflora* as a source of fibre in the production of paper, paperboard and hardboard. Seasoned wood is used for timber products (fence posts, furniture, crafts and corrals) (Tewari *et al.*, 2000). It has potential for gums and resins production. A reddish-amber gum often exudes from the stems and older branches (Harsh, 2011). Tannin or dyestuff can be extracted from P. *juliflora* (Harsh, 2011). In Argentina, Chile and Peru the pods are an important item in making alcoholic drinks such as cocktails (Pasiecznik *et al.,* 2004). P. *juliflora* syrup prepared from ground pods has various medicinal values (Rocha, 1986). It is given to children showing weight deficiency or retardation in motor development and the syrup is believed to increase lactation. It is also used for preparing various medicinal syrups, particularly for expectorants (Rocha, 1986). Tea made from P. *juliflora* is thought to be good for digestive disturbances and skin lesions (Tewari, 2011).

P. *juliflora* has been used to arrest wind erosion and stabilize sand dunes on coastal areas. It is listed as on the tree species used in sand-dune stabilization in India (Harsh, 2011). It is used as shade or shelter when planted in windbreaks and shelterbelts and widely planted for land reclamation because it is an aggressive colonizer, tolerant of very poor, degraded, saline and alkaline soils (Pasiecznik *et al.*, 2001). P. *juliflora* moderately enriches the soil with atmospheric nitrogen obtained through symbiosis with cowpea-type Rhizobium (nitrogen fixing). The roots also form mycorrhizal associations with Glomus fungi. Plants with both Rhizobium and mycorrhizal associations show significantly higher nitrogen fixation rates than those lacking the mycorrhiza (Silva, 1986). It also improves soils organic matter content. P. *juliflora* has been successively intercropped with *Cenchrus ciliaris* and *Pancium maximum* (ICRAF, 1992).

2.5. Climate variability, *Prosopis* spread and pastoral resilience in the drylands

Climatic variability is derived from short to medium term measurements of climate variables (rainfall, temperature, *relative humidity*, atmospheric pressure, wind direction and speed, dewpoint, radiation and soil moisture) (Oglesby *et al.*,2001; IPCC, 2007). It is the variation in the mean state, the standard deviations and the occurrence of climatic extremes on all temporal and spatial scales beyond those of individual weather events (IPCC, 2007). The variation is in time scales of a few years to a few decades, usually shorter than 30 years, a climatic averaging period. Variability may result from natural and anthropogenic processes and these processes can be either internal or external, (Oglesby *et al.,* 2001).

Variability on time scales longer than a few decades (longer than a standard climatic averaging period; 30 years and above) is usually referred to as climatic change (FAO, 2007). Global warming is the deviation of land or sea surface temperatures from the long term mean and anthropogenic activities have been identified as important drivers of increase in “greenhouse” gases (GHG) such as Carbon Dioxide (CO_2). The increase in GHG leads to unpredictable and more intense weather events resulting in climate variability and change phenomenon (Oglesby *et al.,* 2001).

Climate mitigation is an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC, 2004) and climate adaptation is the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2004). Therefore, mitigation reduces all impacts (positive and negative) of climate change and thus reduces the adaptation challenge, whereas adaptation is selective; it can take advantage of positive impacts and reduce negative ones.

Recent climatic variability trends in the drylands of Africa are associated with more frequent and intense droughts that have caused livelihood disruptions of the pastoralists who are the main inhabitants (UNEP/CBD, 2010). Global circulation models predict that, by the year 2100, climate change will increase temperatures by about 4°C in Kenya, leading to massive crop failure, reduced availability of forage and water, livestock mortality and loss of livelihoods (Nanyingi *et al.,* 2012). Droughts have caused livestock deaths worth billions of shillings. Kenya lost livestock worth Kshs. 23 billion and 35 billion in the 2006 and 2009 droughts respectively mainly due to lack of pasture and water (GOK-PDNA, 2012). During the same period, the government spent Kshs.3 billion on livestock feed and supplements as part of drought mitigation strategy. Despite these efforts, the dryland communities still suffered enormous livelihood losses since interventions were implemented late and not in a sustainable manner (GOK- Kenya PDNA, 2012).

Variations in temperature and rainfall patterns have major consequences for biodiversity in the drylands; together with the other stresses from agricultural expansion, alien species invasion and pollution (Kinama *et al.,* 2007). Rainfall has been shown to be variable within season and from season to season; for example in 1996 the rainfall within season dropped to 108mm, which was below average for dryland areas of 250mm of rainfall with consequent crop failure (Kinama *et al.,* 2007). The rains also occur in high erosive storms (Kinama *et al.,* 2007) when vegetation cover is low and soil exposed at the beginning of the rain season. Rainfall is low in amount and poorly distributed over the plants growing season with consequent moisture constrains at critical tasseling or grain filling stages. The soils in most drylands are poor structurally and form surface seal leading to high runoff and low infiltration rates. They are also poor in major plant nutrients. In most drylands, climate change implies increased temperatures, higher soil water evaporation losses (Kinama *et al.,* 2007), sporadic rainfall patterns and increased seasonal aridity, all of which are major determinants of drylands ecological processes.

The challenge of climatic variability in the drylands has been aggravated by the presence of *P. juliflora,* which has invaded the grazing lands in pastoral areas. The plant has shown great tolerance and adapted well to the drylands' extreme and unpredictable conditions (Choge and Pasiecznik, 2006). However studies have shown that if properly managed and utilized, *Prosopis* may be the panacea in providing alternative livestock feed during drought and, therefore, secure dryland livelihoods (Wahome *et al.,* 2008; Pasiecznik *et al.,* 2004)

Pastoralism in Africa have evolved as an adaptation to climate change, and particularly increased aridity (WISP, 2007) and the unprecedented pace of climate change compromises adaptation strategies and is occurring at a time of major changes in resource availability and increased environmental degradation at the global scale. Drylands are mainly found in the world's poorest countries, where people are most reliant on the natural resource base and environmental goods and services, but where their capacity to invest in adaptive technologies is low (UNEP/CBD, 2010). These are the least resilient regions which are projected to bear the biggest burden as a result of climate change (WISP, 2007).

Resilience is the ability of communities and households to anticipate, adapt to or recover from the effects of potentially hazardous occurrences in a manner that protects livelihoods, accelerates and sustains recovery, and supports economic and social development (Resilience Alliance, 2010). The resilience of a system is its capacity to absorb external shocks without suffering a change in state and, therefore, central to the overall productivity of ecosystems. Holling, (1973) defines resilience as the ability of a system to undergo shock and still maintain its on-going functions and controls. Social resilience is the ability of groups to tolerate, survive and respond to environmental and socioeconomic constraints through adaptive strategies (Holling *et al.*, 2002; Bradley and Grainger, 2004) and pastoral adaptive capacity is the cumulative capacity of pastoral households to adjust their livelihoods to multiple and interacting stressors (WISP 2007). Climate variability affects the adaptive capacities and pastoral resilience and *Prosopis* is a viable option in sustaining pastoral resilience through the provision of alternative animal feed resource and trade in carbon credits.

2.6. *Prosopis* biomass production and carbon storage

Biomass is all the amount of live material in a plant. It includes water and other chemicals in the plant. Carbon is an equivalent of charcoal from a tree when all the water is evaporated. Scientists have estimated that about 50% of biomass is equivalent to carbon stocks contained therein (Redondo and Montagnini, 2006).

Vegetation plays a key role in carbon cycle and in maintaining climatic balance (Roy and Ravan, 1996) and biomass quantification is required to understand productivity and changes of vegetation. Vegetation productivity can be estimated either by ground physical measurements or by use of remote sensing techniques (Roy and Ravan, 1996). Carbon sequestration is the phenomenon for the capture and storage of CO_2 by plants to produce biomass, through the process of photosynthesis, thus contributing to global warming mitigation. Carbon dioxide is being released to the atmosphere faster than it is being removed (IPCC, 2007; IPCC, 2004). There are several methods for quantification of sequestered carbon. Many of these methods are not easy to replicate and are limited in their coverage. Such limitations impede sound quantification and monitoring of carbon (Tennigkeit and Wilkes, 2008). Remote sensing has been used to provide answers against such measurement and monitoring limitations and has the potential to meet the requirements for the carbon market; such as permanent sample plots achieved by means of fixed coordinates, coupled with the systematic repetitive characteristic of most satellites. Tucker, (1979) demonstrated that the reflection of the red, green and near-infrared (NIR) radiation contains considerable information about plant biomass.

In carbon markets, 'carbon credits' or 'carbon offsets' are the units of carbon emissions reduced at source. Carbon credit is the currency for trading carbon emissions. The unit for one carbon credit is equivalent to one ton of CO_2 emissions (Tennigkeit and Wilkes, 2008). Purchasers of carbon assets require that the claimed emissions reductions be verified using approved methodology detailing the baseline of CO_2 emissions and a carbon monitoring approach is used. Also a permanence or reversibility assessment to avoid the emission of sequestered carbon is required, (Tennigkeit and Wilkes, 2008). Methods for developing accounting standards for carbon emissions reductions from rangeland management activities have not yet been adequately developed and approved (Galvin, *et al.,* 2004).

Prosopis trees world-wide may account for a significant amount of sequestered carbon, though the tree species in arid and semi-arid zones are not considered when calculating carbon balances at present. Felker *et al.,* (1990) estimated that carbon stored as woody biomass was equivalent to 2-20 t C/ha in *P. glandulosa* stands in the USA, with an additional 1.4-18.4 t C/ha sequestered as reserves of soil carbon, assuming 25% canopy cover (Geesing *et al.,* 2004). While such data is expected to vary greatly between sites and species, they indicate the considerable quantities of carbon stored in *Prosopis* woody biomass and soil reserves. This is yet an unseen value in the emerging global market for ‘carbon credits’.

Currently carbon is valued at US$10 per tonne on average (Reid *et al.,*2004) and modest improvements in management can gain 0.5 tonnes C/ha/yr in the drylands, with *Prosopis* promising a far much better performance (Galvin, *et al.,* 2004). This has the potential to improve pastoral incomes by more than 20% (Reid *et al.,* 2004). Improvements in carbon stocks will also lead to increased biomass and pod production, creating a double benefit” (Reid *et al.,* 2004).

2.7. GIS and remote sensing methods of biomass and carbon stocks estimations

Geographical information systems (GIS) is an organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information (Venus, *et al.,*2006) and remote sensing is the science of acquiring information about the earth's surface without actually being in contact with it (Jeyaseelan, 2003). It is done by capturing and recording reflected or emitted electromagnetic energy; analyzing, and applying that information (Jeyaseelan, 2003). TERRA and AQUA are sensors on board the MODIS (Moderate-resolution Imaging Spectroradiometer), a NASA satellite, which has been operational since 1999. The instruments have 36 spectral bands and cover the world’s land surface in 1 to 2 days. The TERRA and AQUA MODIS sensors are designed to help better understand global land dynamics. Depending on the band, the resolution varies from 250m to 1km. NASA provides daily, weekly and bi-weekly MODIS data, from raw images to value-added products (Reeves *et al.,*2002). Landsat was the first satellite designed specifically to monitor the Earth's surface. The main sensors on the Landsat satellites are the Multispectral Scanner (MSS), the Thematic Mapper (TM), and the Enhanced Thematic Mapper (ETM+). MSS is available on

Landsat 1, 2, 3, 4, and 5. It contains four spectral bands (green, red, and two Near Infrared (NIR) bands) with a spatial resolution of 80 meters. The TM sensor is available on Landsat 4 and 5 and contains seven spectral bands. The ETM+ sensor is available on Landsat7 and contains eight spectral bands. The TM and ETM+ spatial resolution ranges from 15m, 30m, 60m and 120 meters (Zhao and Running, (2010); Zhao *et al.*, 2005).

Remote sensing studies have shown that the integrated vegetation index can be related directly to vegetation amount (above ground biomass) and primary productivity (Tucker *et al.,* 1979). Monteith *et al.,* (1972) presented an analysis of canopy reflectance and its role in studying photosynthesis and transpiration. Canopy reflectance of vegetation is 'causally' related to leaf area index of the canopy and covaries with above ground biomass (Tucker *et al.,* 1979). It is possible to use remote sensing canopy reflectance models for estimating foliage, woody biomass and productive potential (Roy and Ravan, 1996). MODIS, Landsat and SPOT satellites provide broad vegetation type distribution based on major species composition, canopy density and site conditions.

Land cover and soil attributes are expressions of human activities and are essential for a reliable land management database. They are geographical features which form a reference base for applications ranging from forest and range monitoring, production of statistics, planning, investment, biodiversity, climate change, to desertification control (Gregorio and Latham, 2002).

Satellite remote sensing has been successfully used for biomass and productivity estimation (Running, 1986). The unique characteristic of plants is displayed by its reflectance in red and infrared region of electro-magnetic radiation (Jeyaseelan, 2003). These have relationship with the biophysical parameters of plants. Therefore, process based models have been developed to make use of the remotely sensed data available for estimation of net primary productivity (NPP). Production efficiency models are also used to estimate the NPP, which takes Intercepted Photosynthetically Active Radiation (IPAR) and photosynthetic efficiency as input parameters to estimate NPP (Running, 1986; Jeyaseelan, 2003).

Monteith model (Monteith, 1972) has been used to estimate biomass production using the following equation:

NPP=APAR.LUE……………………………………………………….....Equation 2.1

where NPP is the net primary production; APAR is the Absorbed Photo-synthetically Active Radiation; LUE is the Light Use Efficiency factor and PAR is the Photo-synthetically Active Radiation.

The model also uses Normalized Difference Vegetation Index (NDVI).

NDVI = (NIR - Red) / (NIR + Red) ……………………………………....*Equation 2.2*

where NIR (near infra read) and Red are the visible bands of the electromagnetic wavelength (Reeves, *et al.*, 2002), which are used to indicate the level of photosynthetic activity in a green plant.

It is expressed in values in the range of -1 to +1. Healthy vegetation absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light. Studies have shown that PAR and APAR can be derived from remote sensing data by using the NDVI which uses the wavelength in the red (RED) and near infrared (NIR). NDVI=NIR-RED/NIR+RED and APAR/PAR~NDVI. The biomass production per time step can be expressed as NPP=NDVI.PAR.LUE. NPP is measured as total aboveground biomass (Grace *et al.*, 2006)

2.8. Allometric methods of *Prosopis* biomass and carbon estimation

Ground based sampling for estimating biomass in vegetation is an approach which has found acceptability in the recent past (Duff *et al.,* 1994). Some of the commonly employed techniques to estimate biomass are: - the harvest of average sized trees either for the stand or within given size classes; the harvest of all materials in an unit area; and the harvest of individuals over a wide range in size and establishing the relationship between biomass and easily measurable plant parameters, such as, diameter and/or height. The height-diameter at breast height (h-dbh) relationship to biomass in forest stand is well formulated (Lott *et al.,* 2000). Decrease in forest cover brought the need for non-destructive methods for volume/biomass estimation. Methods were developed to relate the biomass with girth, height etc. Component-wise biomass equations were developed, which were used to estimate biomass at the plot level.

Allometric equations are general regression equations widely applied in research. They are generally applied in estimating above ground biomass (AGB). Allometric equations are used to predict tree and stand biomass, based on easily measured tree variables such height, diameters and crown. Normally, developed equations are specific to species, sites, tree age and management (Lott *et al.,* 2000; Rosenschein *et al.,* 1999; Okello *et al.,* 2001), thus limiting their generalized transferability (Muturi *et al.,* 2011; McMurtry *et al.,* 2006).

Muturi *et al.,* 2011, recommended the use of logarithmic linear models recommended for *Prosopis* biomass estimation in the field:

$$\mathbf{(Ln(Fresh\ weight\ (Kg)) = 0.292D30 + 0.59\ (R^2 = 0.94)}\ \ldots\ldots\ldots\ldots\ldots\ldots\ \textbf{Equation 2.3}$$

$$\mathbf{Ln(Dry\ weight\ (Kg)) = 0.2933D30 - 0.03\ (R^2 = 0.92)}\ \ldots\ldots\ldots\ldots\ldots\ldots\ \textbf{Equation 2.4}$$

The equations were derived with basal diameter (D30), diameter at breast height (DBH) and both Height (H) and D30 (HD30).

3. CHAPTER 3: GENERAL MATRERIALS AND METHODS

3.1. The study Area

The study was conducted in the Magadi drylands of Kajiado County (Fig. 3.1), representing about 8% (author's estimate) of the drylands of Kenya affected by *Prosopis*. The study area falls under the inner lowland and lower midland agro-ecological zones, according to Jatzold and Schmidt, (1978). It is sparsely populated except for the agricultural zones of Nkurumani escarpment. The predominant ethnic group is the Maasai, who are mainly pastoralist while few others have adapted to crop farming. This has often posed numerous challenges particularly during periods of drought. The climate is hot and arid and the vegetation is mainly sparse, open bushland. The diverse vegetation cover consists of huge *acacia*, *fig*, and *cordia seninsis* trees among other native species. The under growth consists of bushes and herbs. The area is located in south west of Kenya, bordering Tanzania to the south and Narok County to the west. It is situated within the following coordinates: lat/long. – 1°40'S, 36°E, 2°S, 36°15'E (Fig. 3.1). It has a bimodal rainfall pattern with a an annual total of 460mm and a monthly mean of 50mm, mean altitude of 600m, mean temperatures of 32 °C and generally poor soils which are mainly sandy loam, saline and silt clay. The vegetation is mainly sparse, open bushland, with increasing presence of *Prosopis* being noticed in the recent years

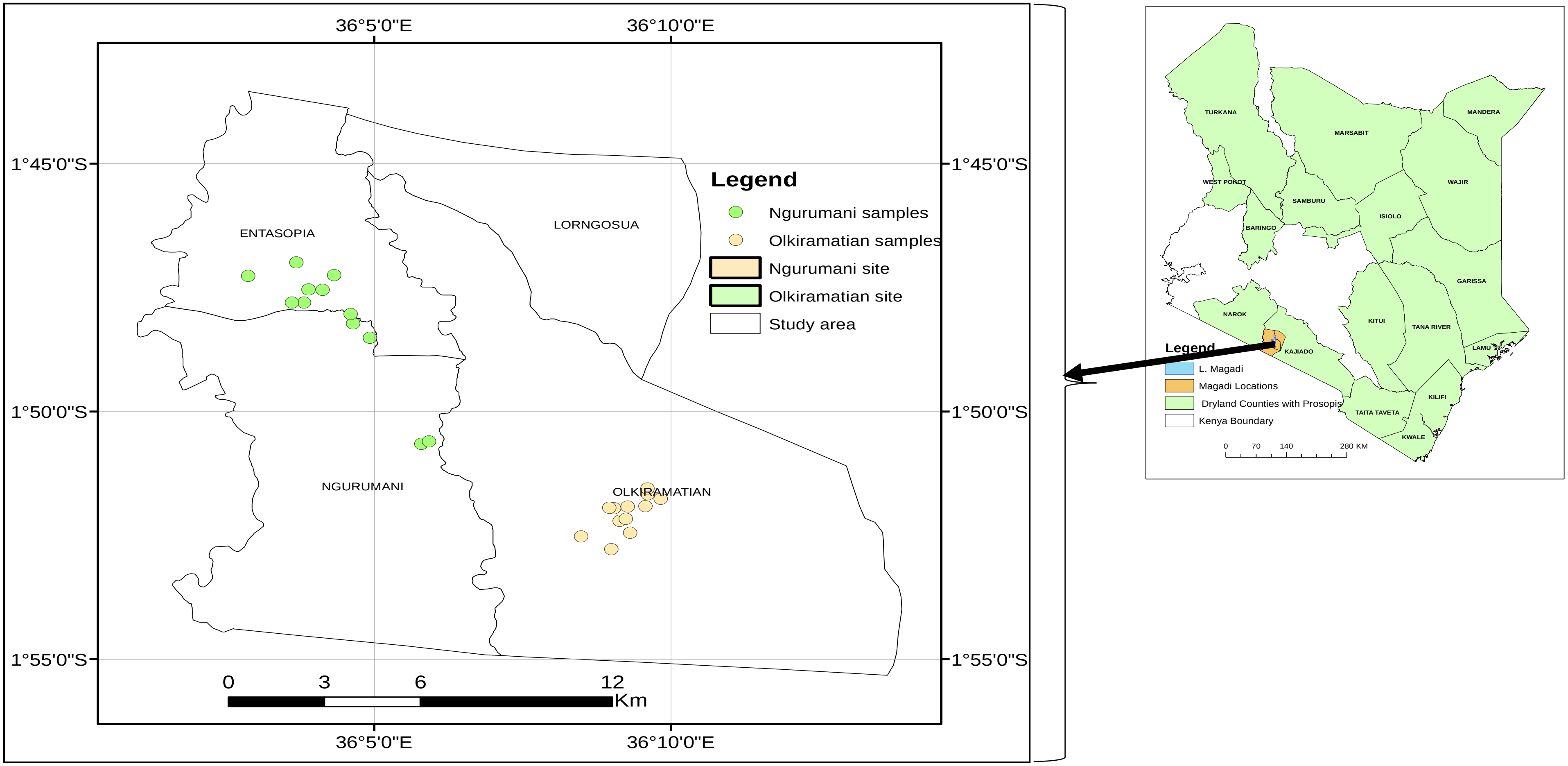


Figure 3.1: Study area in Olkiramatian location of Magadi Subcounty of Kajiado County, Kenya

In Olkiramatian location of Magadi, the landforms are composed of Plains, Plateaus, low gradient foot slopes, medium gradient hills and occasional high gradient hills. The slopes range from flat and wet slopes, gently undulating, rolling and steep slopes and the soils have deep to moderately deep root depth and well to moderately well drained drainage systems. The soil texture is very clay, clay and loam, with occasional sand. The clay types are montmorillonitic, kaolinitic and interstratified clay. The hydrogen ion concentration in a soil solution of soil in water (PH-water) ranges from <4.5-extremely acid to (4.5-4.9)-strongly acid and (7.5-8.4)-moderately alkaline, (8.5-8.9)-strongly alkaline to >9-extremely alkaline (Kenya soil survey, 1997; Sombroek *et al.,* 1980). The landforms are composed of Plains, Plateaus, low gradient foot slopes, medium gradient hills and occasional high gradient hills. The slopes range from flat and wet slopes, gently undulating, rolling and steep slopes (Kenya soil survey, 1997; Sombroek *et al.*, 1980)

Prosopis spread in Magadi division was mainly found in Olkiramatian, Ngurumani, Ol chorro Olepo and Entasopia sublocations of Olkiramatian location. These were the original sites where *Prosopis* was originally introduced in Magadi division between 1989 and 1992. It later spread to other areas in Magadi as follows:-Musenge, Lorngosua sublocations of Olkiramatian location, Kamukuru and Kora sublocations of Ol Donyo-Nyoike location and Lenkobea sublocation of Shompole location (local key informants).

The area under the study covered Olkiramatian, Ngurumani, Ol chorro Olepo and Entasopia sub locations of Olkiramatian location, where there were well established *Prosopis* stands, with adequate dense, moderate and sparse *Prosopis* clusters. Plains and hill slopes landscapes were well represented in these areas.

3.2. Determining the temporal relationship between climate variability, *P. juliflora* spread, livestock population and vegetation cover

3.2.1. Data collection and analysis

A reconnaissance and baseline survey was conducted to delineate *Prosopis* partitions (high density, medium and low density) and identify possible partners (people and institutions). Local informants, (people with social respect in the community and know more about *Prosopis* and its history in Magadi division), were sought. Information on young Maasai youth to serve as potential field assistants and the perceptions of the local people about *Prosopis* and their cooperation during the period of study was also established.

Climate data for 20 years (temperature, rainfall) from meteorological stations, Magadi Soda Ash Company and South Rift Association of Land Owners (SORALO) field station; and livestock population data from Kenya national bureau of statistics (KNBS, 2010), central bureau of statistics (CBS) and livestock offices in Magadi, Kajiado and Nairobi) were collected and used to determine rainfall and temperature trend relationships.

Vegetation cover and *Prosopis* data for the same period: - normalised difference vegetation index (NDVI), net primary productivity (NPP) from MODIS satellite images (Piedad, *et al.*, 2007; NASA), land use, land cover from FAO africover (Gregorio and Latham, 2002) and soil data (Kenya soil survey, 1997). GPS data and GIS databases from ILRI, DRSRS, NDMA, Regional centre for mapping (institutions dealing with spatial data) were used.

In determining trends over the period, the following data analysis methods were used:- vegetation types and trends - MODIS satellite images (NDVI, NPP), land use, land cover and soil data, GPS data, GIS databases. To establish the start, spread and quantities of *Prosopis* in the area, MODIS satellite images were used to derive NDVI and NPP. The NDVI was used to identify the vegetation types which are photosynthetically active through the wet and specifically during the drought periods. These vegetation types were highly likely to be *Prosopis*. Land cover, soil data, GPS data, GIS databases were used to identify areas with the suitability characteristics for *Prosopis* to thrive.

NDVI is an indicator of vegetation health status (greenness). High NDVI values (greater than 0.7) obtained during the dry periods of the year (January to March and June to September) was isolated to be indicative of *Prosopis*, which remains green during the dry periods when all other vegetation types have dried up or shed leaves due the dry environmental conditions. The preference of *Prosopis* to saline soils and flood plains was also used to further identify and define *Prosopis* stands in the satellite images. The preference of *Prosopis* to riverine areas; sparse and dense vegetation areas, woodlands and grasslands was further used in identifying *Prosopis*. Sensitivity to altitude was also used to delineate *Prosopis* areas. Ground GPS calibrations and validations were eventually used to confirm the presence of *Prosopis juliflora* in the field. The Monteith model was then applied to determine the biomass quantities.

To establish the disappearance of other plant species, MODIS satellite images (NPP, GPP), land use, land cover and soil data, GPS data, GIS databases were also used. Comparisons of trends of climate data, livestock population, *Prosopis* and other vegetation cover were done using Excel spreadsheets to establish relationships.

Descriptive statistics were used to examine data distribution. To determine relationships between trends in climate data, livestock population data, *Prosopis* and other vegetation cover, correlations and regression analysis were used.

3.3. Estimating above ground *P. juliflora* biomass and carbon stocks

3.3.1. Field experimental layout and data collection

Two (2) *Prosopis* landscape strata of hillslopes and floodplains were selected purposively. Within each landscape, three (3) sites containing sparse (less than 30%) *Prosopis* density, moderate *Prosopis* density (50-70%) and high *Prosopis* density (greater than 70%) were identified purposefully. The density was validated through mapping (delineation) of areas occupied by *Prosopis* using satellite images (MODIS (250m) derived NDVI), land use & land cover and GPS data. For each site, a grid of plots ($30m^2$) was laid out on topo maps. Each plot in the grid was allocated a unique number to enable randomisation.

Each site had four (4) random plots of 30mx30m randomly selected and fenced off except for the high density site, where an additional four plots were selected and managed (pruning and 5m spacing between the *Prosopis* trees). The total number of plots in the whole study area of both landscapes was (2*(4+4+4+4)) = 32

3.4. Delineation and selection of *Prosopis* sampling sites and units

Local community informants were used in participatory mapping to delineate *Prosopis* density strata into hillslopes and floodplains strata in the purposefully selected landscapes. They were also used to identify sparse, moderate and dense *Prosopis* density sites. The mapping was done on the area topomap sheet with a scale of 1: 50,000. The identified *Prosopis* strata and sites were then digitised in GIS software (ArcGIS) to create GIS shapefiles of *Prosopis* density strata and sties. The *Prosopis* density shapefiles was then partitioned using square grids and each grid assigned a unique number. MS Excel was then used to generate four (4) random numbers from the unique numbers in each of the three *Prosopis* density sites. The random numbers generated were used as the identifiers of the randomly sampled observation points, where a 30mx30m plot was demarcated, fenced and all the field observations (allometric variables and pods weights) done on it. In the dense *Prosopis* density site, two (2) 30mx30m plots were demarcated side by side. Management practices were applied (pruning and spacing) in one of the two plots and the other plot was left in the natural state.

3.5. Management of sampling plots

The managed plots were selected in advance and demarcated as such. The management consisted of pruning (2-3 stems per plant) and thinning to space (5m apart) of the naturally occurring trees. Any vegetation undergrowth and re-growth was regularly removed in the managed plots. The management was done for ten months, during the study period. Unmanaged plots were those where the observations were taken on the naturally occurring trees with no management practices applied.

The *Prosopis* shrubs and trees (plants above 3m in height and producing pods) in each observation plot were identified and counted. Ten (10) *Prosopis* shrubs and trees in each plot were randomly selected (sampled) and basal diameter (m), breast height diameter (m), tree height (m) and crown diameter (m) taken once every month. Ground *Prosopis* biomass was estimated using previous allometric equations by Muturi *et al.*, (2011), among others. The area covered by each sampled *Prosopis* tree was estimated using the crown diameter. The total area occupied by the *Prosopis* trees in one plot was determined by extrapolating the area occupied by the sampled trees to the whole plot. This was done by multiplying the total number of *Prosopis* trees in the whole plot by the area occupied by the sampled trees and divided by sample size. The area occupied by the *Prosopis* shrubs and trees and the biomass quantities in the whole study was the summation of the each plot measurements of area and biomass.

Field observations and recordings in the *Prosopis* landscapes was carried out (replicated) in each of the 32 plots (8 managed and 24 unmanaged). In the managed plots, stems were thinned and pruned (2-3 stems per stump) and spaced at 5m. Measurements of diameter at base and breast height (DBH), tree height and crown diameter, all in meters (m) was taken in the managed and unmanaged plots. The number of *Prosopis* tress in each plot was counted, recorded and measurements (DB, DBH, crown diameter, height) of ten (10) representative *Prosopis* trees (random samples) once every month for one (1) year were done for both managed and unmanaged plots. Six (6) casuals were hired, three (3) per landscape to manage and maintain the *Prosopis* plots. They were responsible for making observations and recording. They were also be responsible for maintaining the plots fencing, removing the undergrowths and re-growths. One casual in each landscape supervised the rest.

3.6. Data analysis for biomass production and carbon stocks

MODIS (250m) satellite derived NDVI and NPP were used in Monteith equation (Monteith *et al.,* 1977) to estimate the biomass quantities. Land use, land cover and soil data, GPS data, GIS databases were used to delineate areas of suitable environmental characteristics for *Prosopis* to thrive. These datasets were used to enhance the accuracy of identifying the areas covered by *Prosopis* and determining biomass quantities.

Allometric equations to determine biomass from the physical parameter measurements (BD, DBH, tree height and crown diameter) were also used. Muturi *et al.,* (2011) recommended the logarithmic linear D30 models for *Prosopis* biomass estimation in the field

Ln(Fresh weight (Kg)) = 0.292D30 + 0.59……………………………Equation 3.1

A biomass fraction of 0.5 was used to estimate *Prosopis* based carbon stocks as this is an accepted estimation (Redondo and Montagnini, 2006). GPS points were captured for calibration, validation and ground truthing. Descriptive statistics (means, medians and scatter plots) for distribution analysis and split-plot ANOVA were used to test for differences between the repeated measurements of biomass production in the managed and unmanaged plots, moderate and sparse *Prosopis* plots.

3.7. Data collection and analysis methods for estimating pods production

Measurements were done on the unmanaged plots (these were the natural *Prosopis* stands with minimal disturbance). They were twenty four (24) out of the 28 plots) of 30x30m, whose centres are the GPS points, taken in the field. Measurements were also done on managed plots (4 in number). Thinning, pruning (2-3 stems per stump) and spacing (4m) on randomly selected four (4) out of the 28 plots of 30mx30m, whose centres are the GPS points, taken in the field were applied on the managed plots.

Pods were collected and weighed in kilograms (kgs) in each plot once a week for one wet and two dry seasons in the managed and the unmanaged plots. The plots were fenced off to prevent interference from the animals and human beings. Measurements of pod quantities, base diameter, DBH (m), crown diameter (m), crown heights (m) were taken. The measurements were taken once every week for the pods and once every month for the DBH, crown diameter and crown heights.

For data analysis, descriptive statistics (means, medians) were used for pods production distribution analysis. Comparison of the differences between pods production in the managed stands and the unmanaged stands and between trends in pods and biomass production in managed and unmanaged areas were done.

3.8. Study outputs

The relationships established between trends in climate variability (rainfall, temperature), livestock population growth and vegetation cover dynamics with *Prosopis* colonization informed policy on climate change adaptation and mitigation. A Biomass and Carbon stocks assessment methodology was developed to encourage *Prosopis* based carbon credits trade and information on *Prosopis* pods productivity informed policy formulations toward the use and commercialization of *Prosopis juliflora* pods as alternative of animal feeds resource.

Four (4) scientific papers were submitted for publishing in peer reviewed journals. These included: Relationship between *Prosopis* spread and livestock population dynamics and climate variability; spatial and temporal spread of *Prosopis juliflora* using remote sensing derived NDVI and NPP products; *Prosopis* biomass estimation using allometric equations; and Seasonal *Prosopis* pods production. A thesis as partial requirement for the PhD degree in Dryland Resource Management was produced. The study further enhanced the utilization of *Prosopis* products for building pastoral resilience and climate variability adaptation.

4. CHAPTER 4: TEMPORAL RELATIONSHIP BETWEEN CLIMATE VARIABILITY, *PROSOPIS JULIFLORA* INVASION AND LIVESTOCK NUMBERS IN THE DRYLANDS OF MAGADI, KENYA

4.1. Abstract

A study was conducted to determine the association of climate variability, *Prosopis juliflora* spread, and other vegetation trends with livestock population dynamics in Kajiado County, Kenya. Monthly rainfall, mean monthly temperatures, cattle, sheep and goats populations from January 2000 to December 2014, were analyzed to determine time series trends. Normalized Difference Vegetation Index (NDVI) data derived from moderate resolution imaging spectroradiometer (MODIS) 250m satellite imageries for 2000-2014 were used to determine the temporal dynamics of *P. juliflora* invasion in the study area. Both temperature and rainfall trends showed marked variability over the period under study. The mean monthly temperatures during the long dry season increased erratically from 33^0C in 2000 to 37^0C in 2014. Moreover, the rainfall during the wettest season were 600mm in 2000 and 250mm in 2014. During the study period, divergence from the long term mean rainfall (450mm) decreased from 585mm to 403mm. At the same time cattle population decreased, while sheep and goats populations remained static. *P. juliflora* invasion correlated positively ($r=0.2$; $P<0.05$) with mean monthly temperature and negatively ($r=-0.4$; $P<0.05$) with rainfall and other vegetation cover in drier parts but not in the higher altitude and wetter parts of the study area. It also correlated negatively with cattle populations ($r=-0.4$; $P<0.05$). In the 1980's, bushlands and woodlands constituted 95% and 5% of the land cover, while in in 2008, herbaceous vegetation, shrublands, and open trees together with bare areas constituted 50%, 30% and 22% respectively; out of which 70% had been taken over by *Prosopis* in 2014. This study demonstrated that even though the trends showed that cattle population decreased as climate variability and *Prosopis* invasion increased, there was no significant correlation among the attributes, over the period under study.

Keywords: Climate variability, drylands, livestock, *Prosopis juliflora*, vegetation cover, trends

4.2. Introduction

After introduction to Africa in the 1820s and in Kenya in the 1970’s and 1980’s (Wahome *et al.*, 2008; Choge and Pasiecznik 2006), *Prosopis juliflora* (Sw.) DC has been aggressively invading grazing and farm lands (Tewari *et al.,* 2000; Pasiecznik *et al.,* 2001). Efforts to eradicate it have not succeeded anywhere in the world. Due to its hardiness and versatility, it grows fast in such areas as dry degraded grasslands and wastelands with scanty and erratic rainfall, shifting sand dunes, eroded hills and river beds and saline terrains, and spreads, where virtually no other trees survive (Silva, 1986).

Increased climatic variability trends in the drylands of Africa, associated with frequent and intense droughts, increased proportions of degraded lands that disrupted livelihoods of pastoralists (UNEP/CBD, 2010). Thus climate change is costly and predictions are that both it and its cost will escalate (Nanyingi *et al.,* 2012). The key costs emanate from livestock deaths and displacement and suffering of human populations (GOK-PDNA, 2012). Despite such costly interventions as free provision of livestock feed and supplements, the dryland communities still suffer enormous livelihood loss (GOK-PDNA, 2012). Climate variability and population increase in the pastoral areas have contributed to the degradation of grazing lands (Kazmi et al 2010) that has led to changes in vegetation cover and *Prosopis* invasion further aggravating the livelihood challenge. Reports that exist fail to address specific plant species habits towards climate variability (Galvin *et al.,* 2004; IPCC 2007; Resilience Alliance, 2010; Tennigkeit and Wilkes, 2008; WISP Policy Note No. 04, 2007).

Spread of *Prosopis juliflora* was observed since 1994 in Olkiramatian location of Magadi division of Kajiado County. The spread was noted to have some effects on indigenous vegetation species and livestock populations. The objective of this study was to evaluate the realtionships between *Prosopis* spread patterns, climate variability, vegetation cover trends and livestock population dynamics in the drylands.

4.3. Materials and methods

4.3.1. The study Area

The study was conducted in Olkiramatian location of Magadi division - Kajiado County. The area is located in south west of Kenya, bordering Tanzania to the south and Narok County to the west. It is situated at altitude of 600m within lat/long. – 1°40'S, 36°E, 2°S, 36°15'E (Fig. 3.1), under the inner lowland and lower midland agro-ecological zones (Jatzold and Schmidt, 1983). It has a bimodal rainfall pattern with an annual total of 460mm and a mean of 50mm, mean temperatures of 32 °C. The soil texture is very clay, clay and loam, with occasional sand. The clay types are montmorillonitic, kaolinitic and interstratified clay (Kenya Soil Survey, 1997). The landforms are composed of plains, plateaus, low gradient foot slopes, medium gradient hills and occasional high gradient hills (Gregorio and Latham, 2002). The slopes range from flat and wet slopes, gently undulating, rolling and steep slopes. The vegetation is sparse, open bushland, with increasing presence of *Prosopis* (Gregorio and Latham, 2002).

The Olkiramatian plains in Olkiramatian sublocation, recieves 400mm of rainfall annually, mean temperatures of 35^0C and a vegetation cover of mainly shrubs, *Prosopis* and bare land. The Ngurumani hill slopes in Ngurumani sublocation receive 600mm of rainfall annually with mean temperatures of 28^0C and vegetation dominated by bushland, *Prosopis* and irrigated crop fields.

4.3.2. Data types and sources

Rainfall and temperature data were collected and collated from Makindu and Narok meteorological stations climate data recorded over 30 years (1982-2012); National drought management authority (NDMA) - Kajiado county climate data for 7 years (2007-2013); Magadi Soda Ash Company climate data for 50 years (1964-2013); Kajiado Maasai Rural Center (Isinya) climate data for 23 years (1981-2014). Olkiramatian climate data (local weather station manned by South rift association of land owners (SORALO) for 5 inconsistent years (2008-2014). The Olkiramatian climate data was used to validate the meteorological stations of Narok and Makindu, Kajiado county (NDMA) climate data Magadi Soda Ash company climate data and the Kajiado Maasai Rural Center (Isinya) climate data.

Vegetation and Prosopis productivity data, derived from the Terra MODIS (Zhao and Running. (2010); NASA:https://lpdaac.usgs.gov/products/modis_products_table/mod13q1) series vegetation indices Normalized Difference Vegetation Index (NDVI) satellite data (Reeves, et al 2002), was used. NDVI data was downloaded from the ENDELEO website (http://endeleo.vgt.vito.be/), unzipped and reprojected in ArcGIS (ArcGIS: http://www.esri.com/software/arcgis/arcgis-for-desktop). Magadi division and Olkiramatian location vegetation extends were extracted using ArcGIS tools. The vegetation data - NDVI with spatial resolution of 250m for the period of 14 years (2000 – 2014) and temporal resolution of 30 days (one month) from MODIS satellite images was analysed for vegetation and *Prosopis* trends. Land use, land cover and soil data, field GPS data, and GIS databases from Regional Mapping Center - Kasarani, International Livestock Research Institute (ILRI), Department of Remote Sensing and Resource Surveys (DRSRS), Food and Agriculture Organization (FAO) and Kenya Soil Survey – institutions dealing with spatial data were also used in determining vegetation and

Prosopis patterns. Participatory mapping of *Prosopis* clusters was done with help of local key informants who composed of three elderly men, one woman and one young man.

Livestock population data were obtained from the annual livestock population collected and collated from Kajiado County livestock offices, Magadi Division Livestock Offices and DRSRS in Nairobi for the period 1980– 2013.

4.3.3. GIS and remote sensing methods for estimating vegetation biomass

MODIS satellite derived NDVI images (Jenkerson *et al.*, 2010) were used to establish the spread patterns of *Prosopis*. The NDVI was used to identify the vegetation types which were photosynthetically active during the drought periods. These vegetation types were most likely *Prosopis* plants. Land cover, soil data, GPS data, GIS databases were used to identify areas with the suitability characteristics for *Prosopis* to thrive.

$$\mathbf{NDVI = (NIR - Red) / (NIR + Red)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{Equation\ 4.1,}$$

where NIR (near infra read) and Red are the visible bands of the electromagnetic wavelength (Reeves *et al.*, 2002).

NDVI has been used to indicate the level of photosynthetic activity in a green plant (Grace *et al.*, 2006). It is expressed in values in the range of -1 to +1. Healthy vegetation absorbs most of the visible light that hits it, and reflects a large portion of the near-infrared light. Unhealthy or sparse vegetation reflects more visible light and less near-infrared light (Grace *et al.*, 2006). It is an indicator of vegetation health status (greenness).

High NDVI values (greater than 0.7) obtained during the dry periods of the year (January to March and June to September) were used to isolate *Prosopis*, which remains green during the dry periods when all other vegetation types have dried up or shed leaves due the dry environmental conditions. Values lower than 0.1 typically correspond to areas with little or no vegetation (rocks, ice, and desert). Moderate values (around 0.2 and 0.3) correspond to shrub and grasslands and high values (0.5 and above) typically correspond to dense vegetation like rainforests (Rahman and Dedieu, 1994; Huete *et al.,* 2002)

The preference of *Prosopis* to saline soils and flood plains was also used to identify *Prosopis* stands in the satellite images. The preference of *Prosopis* to riverine areas; sparse and dense vegetation areas, woodlands and grasslands was further used to help in delineating *Prosopis* occupied areas.

To establish the disappearance of other plant species, MODIS NDVI images, land use, land cover and soil data, GPS data, participatory mapping of *Prosopis* clusters using community opinion leaders and GIS databases were used. Comparison of climate data trends, *Prosopis,* other vegetation cover and livestock population was done using Excel spreadsheets to establish relationships. This was done using previously developed techniques (Tucker *et al.*, 1979; Sellers 1985; Roy and Ravan 1996; Gregorio and Latham 2002; Running 1986; Jeyaseelan 2003).

Ground GPS data was collected and used to calibrate and validate the presence of of *Prosopis juliflora* in the different levels of *Prosopis* invasions of the two landscapes of Olkiramatian plains and Ngurumani hillslopes. The two landscapes of the study area were identified purposively. Each landscape contained three (3) sites containing sparse (less than 30%) *Prosopis* density, moderate *Prosopis* density of 50-70% *Prosopis* and high *Prosopis* density (dense) of greater than 70% *Prosopis. These* were identified with the help of the knowledgeable local informants using participatory mapping and topomaps. GPS points were taken in each site with the help of research assistants. They were used for spatial data overlay analysis, ground truthing and verification using GIS tools.

4.3.4. Data analysis

Climate data (mean temperature and total rainfall), livestock population data and vegetation and *Prosopis* productivity datasets for the period 2000 – 2014 were plotted against time to establish trends over the study period. Regression analysis was done for rainfall, temperature, *Prosopis* biomass and livestock population trends against time in Olkiramatian location of Magadi sub county, Kenya.

Correlations analyses were done to determine the longitudinal relationships between trends in rainfall and temperature and livestock population, *Prosopis* and other vegetation cover. Strength and direction of the relationships were tested, while descriptives (standard deviation, mean, range and coefficient of variation (C.V.)) were determined for all variable relationships.

Multiple correlations were done for the monthly and dry season time series of the vegetation and *Prosopis* productivity (NDVI) data for the period 2000 – 2014; climate data (monthly rainfall totals and mean temperatures) and livestock populations.

4.4. Results and discussions

4.4.1. Rainfall and temperature variability in the study area

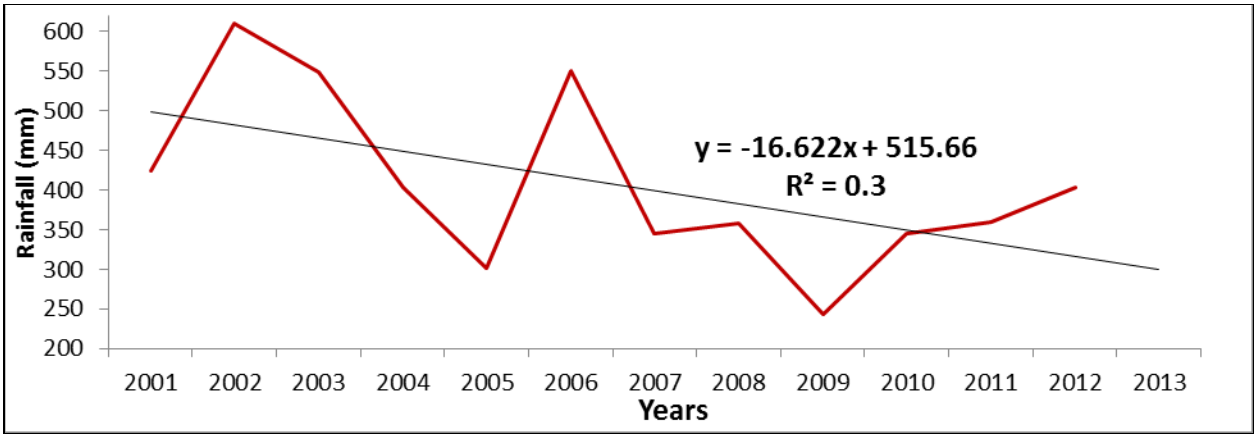
Long term annual rainfall amounts for Magadi division were plotted against time and a trend line developed. It showed that the rainfall amounts were varying and have been on the decline over time (Fig. 4.1a). The standard error (SE) of 96 (Table 4.1a) and the small R^2 of 0.30 (Fig. 4.1a) shows there was high rainfall variability. Further, the results were similar to research done in Eastern Kenya which showed that rainfall variability occurs within the season, from season to season, from place to place and even from year to year to year (Kinama *et al.,* 2007). Distribution of rainfall is very important and rainfall variability is the main limiting factor in biomass production as it causes variation in biomass formation. Infact the yield of maize stabilized with even rainfall distribution and increased with increasing rainfall amounts (Kinama *et al.*, 2007).

Seasonal rainfall trends in a year in Magadi were analysed. The seasons were January to February (short dry season), March to May (long rain season), June to September (long dry season) and October to December was the short rain season (Agnew, *et al.,* 2000). Droughts are the major climatic conditions which affect vegetation and livelihoods in the ASALs. It was in the dry periods when the effects of water shortages are most apparent. Among the effects was the low vegetation quality and quantity (GOK-PDNA, 2012).

A declining trend in the rainfall amounts was observed over the period under study - period of 13 years (Fig. 4.1a), The R^2 values of 0.3 showed there was high rainfall variability during the dry seasons. This has direct implications on the vegetation, livestock and livelihood dynamics
A plot of the annual mean temperatures for the period 2001 to 2013 against time (Fig. 4.1b) revealed an increase in average temperatures over the study period. A high and positive relationship between temperature and time (R^2=0.75) and standard error of 0.86 (Table 4.1b) was observed. Possible effects for the rise of temperatures are the depressed vegetation growth for less drought tolerant plants, dominance of the aridity tolerant plants such as *Prosopis juliflora* and high water losses through evapotranspiration (Kinama *et al.,* 2005). Elsewhere, other studies in the ASALs showed that soil evaporation can take upto 50% of seasonal total rainfall (Kinama *et al.*, 2005). Temperature rises have increased over the years and contributed to global warming.

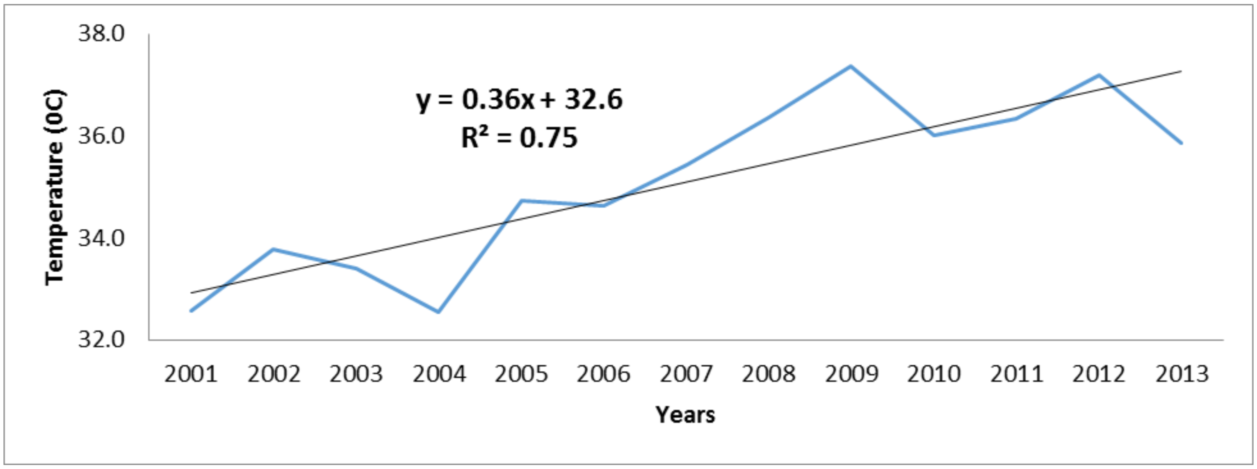
4.4.2. Land cover changes in Olkiramatian location

A shift from woodlands and bushlands in the 1980s to shrublands, herbaceous cover and bare lands in the 2000s was evident in land cover change analysis in Olkiramatian location (Fig. 4.2a).



Source: MSC Meteorological Department, 2014

Figure 4.1a: Annual rainfall (mm), trends in Olkiramatian location of Magadi Subcounty Kenya (2001 - 2013)



Source: MSC Meteorological Department, (2014)

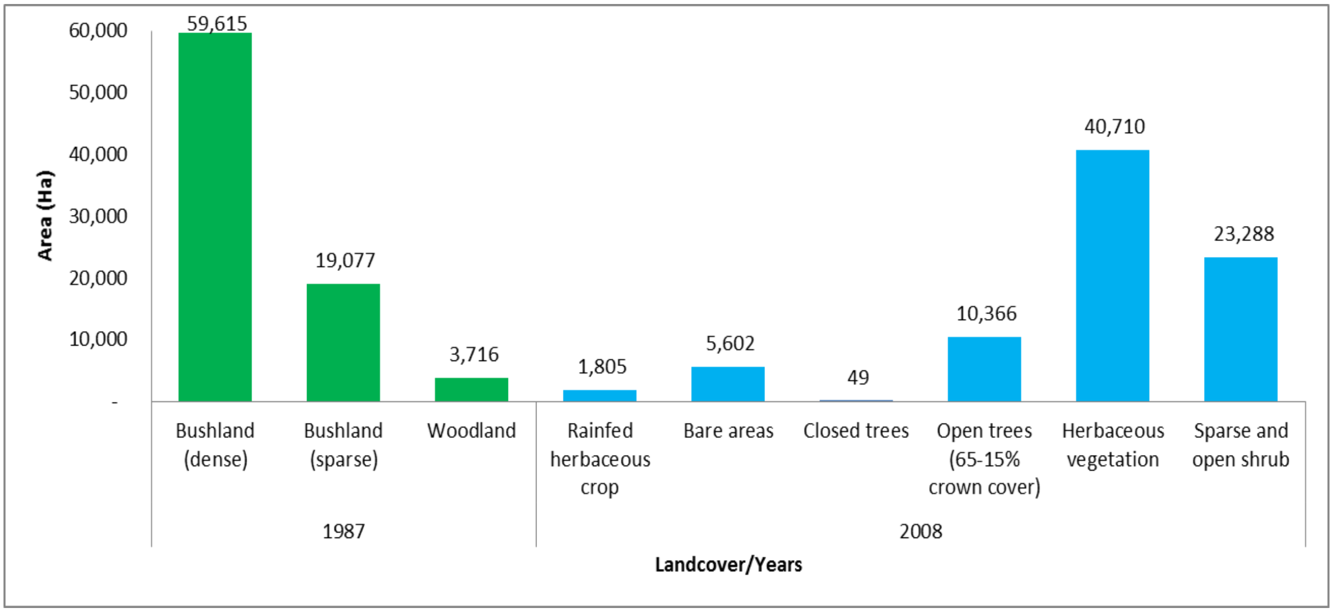
Figure 4.1b: Annual average temperatures in Olkiramatian location of Magadi Subcounty Kenya (2001-2013)

This could be attributed partly to the declining rainfall amounts, the raise in temperatures and increased human activity (land use). The shrublands, herbaceous cover and bare lands land cover of the 2000's has been taken over by *Prosopis juliflora* in 2014 by upto 70% of the landcover (Fig. 4.2b)

4.4.3. *Prosopis juliflora* trends in the floodplains and hillslopes

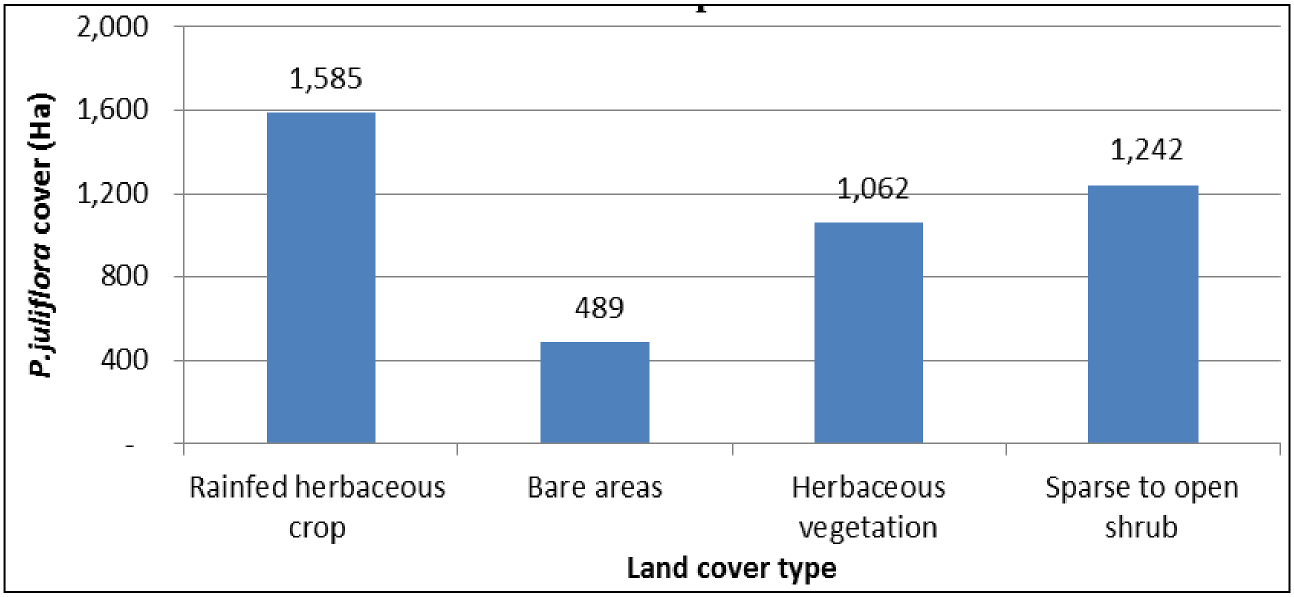
During the dry seasons, most of the indigenous (native) plants productivity is depressed. *Prosopis juliflora* was introduced in Olkiramatian between 1989 and 1994 and it is able to tolerate very difficult environments including very arid (hot and dry) areas, saline and sandy soils (Pasiecznik *et al.,* 2004). In addition it produces large number of pods containing very many seeds (Wahome *et al.,* 2008). It is always green when most of the other vegetation types have either dried up or shed their leaves to cope with drought. The *Prosopis* clusters digitized from the participatory mapping of *Prosopis* locations and the GPS points of the randomly selected field 30mx30m *Prosopis* plots were used to extract *Prosopis* NDVI values from the general vegetation NDVI values in the MODIS 250m images, using ArcGIS software. *Prosopis* NDVI values were extracted for both the short and long dry seasons.

NDVI values declined for the periods between 2006 and 2009, then a steady increase in the NDVI upto 2014 (Fig. 4.3a) in Olkiramatian. This could be partially attributed to the depressed rainfall upto 2009 (Fig. 4.1a) when there was a severe drought in this area. After 2009, the NDVI started to rise at a faster rate. Overall, there was modest increase (R^2=0.45) in *Prosopis* productivity during the period under study.



Source: Analysis based on FAO Africover databases (1987 - 2008)

Figure 4.2a: Vegetation cover change from 1987 to 2008 in Olkiramatian location of Magadi Subcounty, Kenya

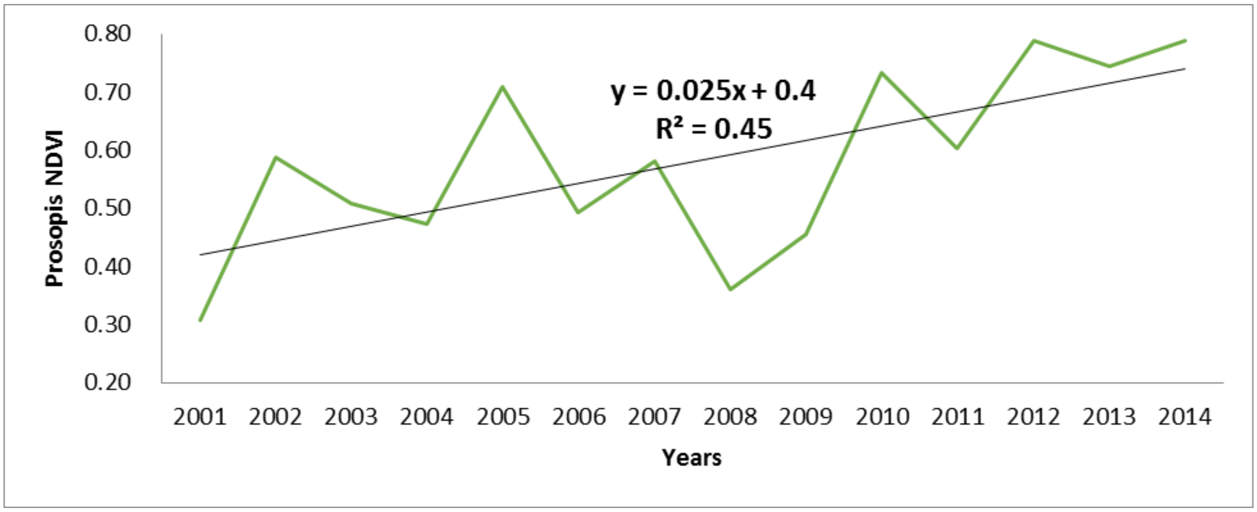


Source: Analysis based on FAO Africover databases, 2008

Figure 4.2b: Area (ha) invaded by *Prosopis* in 2014 in Olkiramatian location of Magadi Subcounty, Kenya

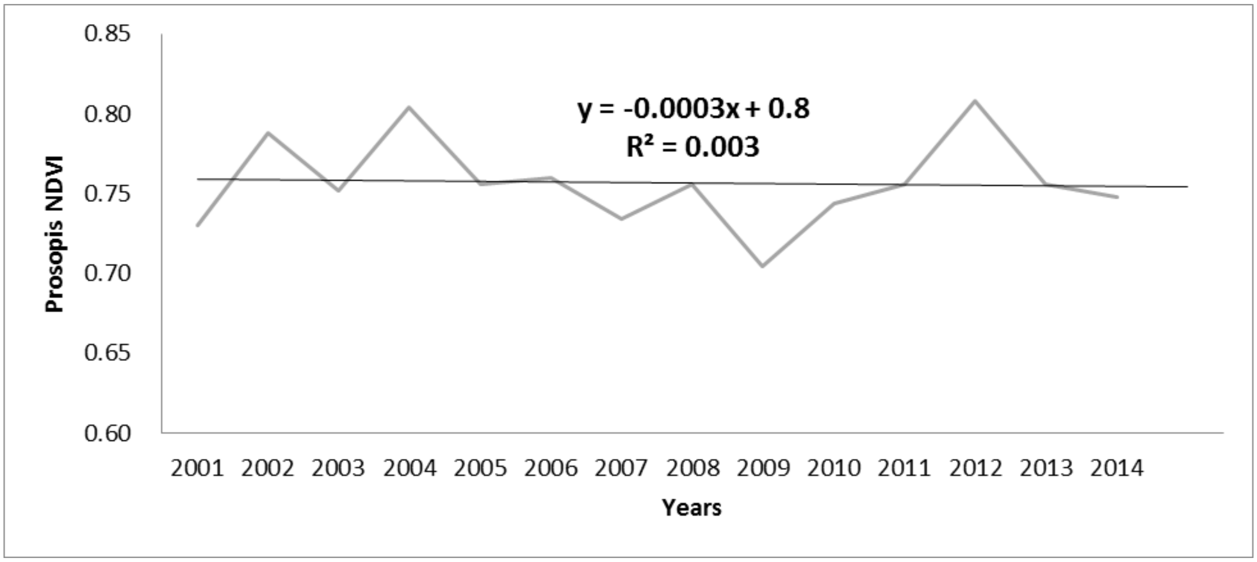
This observation could be further explained by the tolerant behavour of the *Prosopis juliflora* to aridity and saline soils; its deep and laterally spreading rooting system in reaching out to ground water and rain water runoff respectively (Pasiecznik *et al.,* 2001). Following its introduction in the early 1990s', *Prosopis* was not competitive enough to suppress the other vegetation types until the 2006 - 2009 droughts. After 2009, *Prosopis* was more dominant and competitive owing to its superior adaptive capacity to arid conditions (Pasiecznik *et al.,* 2004). The annual rainfall amounts were declining during the entire monitoring period from 585mm to 403mm (Fig. 4.1a).

The low value (R^2=0.003) suggested that there was less fluctuation of *Prosopis* trends but there was high values in *Prosopis* NDVI in Ngurumani (Fig 4.3b). Ngurumani hill slopes, the traditional dry season grazing area of the local Maasai community, receives moderately higher rainfall amounts than the Olkiramatian plains (Agnew *et al.,* 2000). It has numerous natural springs flowing throughout the year (Agnew *et al.,* 2000). In the early 2000s' much of its woodlands and bushlands were opened up for irrigated agriculture (Agnew *et al.,* 2000). The combination of the opened spaces, saline soils, Ewaso Ngiro riverine ecosystem and the severe droughts of the late 2000s' encouraged *Prosopis* colonization. Although *Prosopis* was colonizing the area at a faster rate, it had not reached the stage where it could competitively suppress the other vegetation types. This was due to the availability of relatively adequate water sources to enable other plants to compete favorably. The high NDVI values (greater than 0.75, Fig 4.3b) was an indication that there were favorable conditions for *Prosopis* to thrive, notably good supply of water. *Prosopis* biomass trends in both Olkiramatian and Ngurumani were further explained with regression parameters in table 4.2 (R^2 =0.45 and 0.003 in Olkiramatian and Ngurumani respectively, while the respective standard errors were 0.12 and 0.03.



Source: Author's analysis based on MODIS 250m data (2001-2014)

Figure 4.3a: *Prosopis* NDVI trends from 2001-2014 in Olkiramatian floodplains, Magadi Subcounty, Kenya



Source: Author's analysis based on MODIS 250m data (2001-2014)

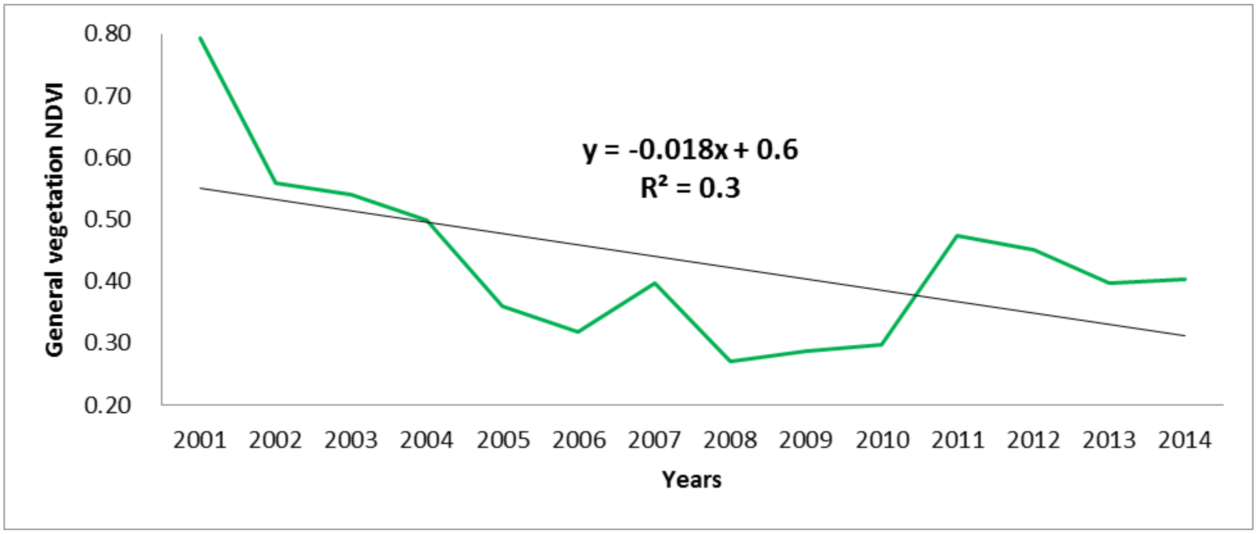
Figure 4.3b: *Prosopis* NDVI trends in Ngurumani hillslopes of Magadi Subcounty, Kenya (2001-2014)

4.4.4. Other vegetation trends

NDVI values for the other vegetation for the period 2000 to 2014 were plotted against time (years) - Fig. 4.4a and Fig.4.4b) in the floodplains of Olkiramatian sublocation and the hillslopes of the Ngurumani and Entasopia sublocations in Magadi Subcounty.

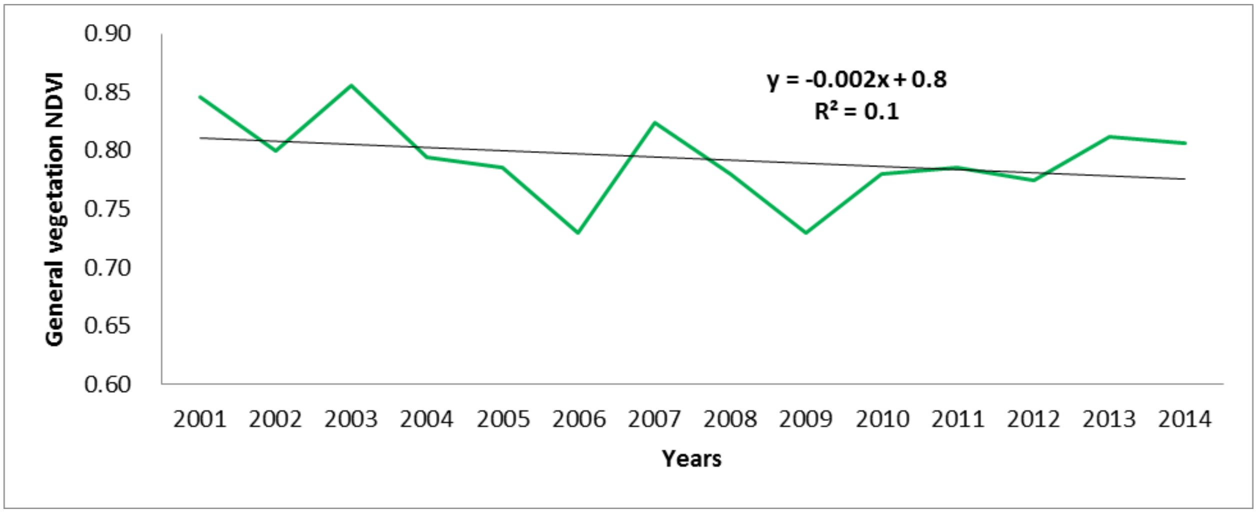
The NDVI values in the Olkiramatian plains declined in that period (Fig. 4.4a), while there was little change (less fluctuations) to the NDVI values for the Ngurumani hillslopes (Fig. 4.4b) for the same period. This could be attributed to the lower rainfall amounts in the Olkiramatian plains (Fig. 4.1a) and the higher rainfall amounts and the numerous natural springs in the Ngurumani hill slopes (Agnew *et al.,* 2000). It could also be as a result of the competitive advantage of the drought resistance plants e.g. *Prosopis juliflora* in the water stressed plains as opposed to the hillslopes.

There was an observed decline in the NDVI values upto the period between 2006 and 2009, then a steady increase in the NDVI upto 2014 (Fig. 4.4a). This could be attributed to the depressed rainfall upto 2009 when there was a severe drought in Olkiramatian. After 2009, the NDVI rose at a slower rate. The overall NDVI trends of the general vegetation are in the decline, in line with the depressed rainfall amounts. In Ngurumani, other vegetation NDVI trends have little fluctuations due to the higher moisture levels in Ngurumani (Fig. 4.4b). This mirrors the landcover change trends, where the cover changed from woodlands and bushlands in early 1980's to open trees, herbaceous vegetation, shrublandas and bear lands in 2000's (Fig. 4.3a).



Source: Author's analysis based on MODIS 250m data (2001-2014)

Figure 4.4a: General vegetation NDVI trends (2001-2014) in Olkiramatian plains of Magadi Subcounty, Kenya



Source: Author's analysis based on MODIS 250m data (2001-2014)

Figure 4.4b: General vegetation NDVI trends (2001-2014) in Ngurumani hill slopes of Magadi Subcounty, Kenya

Vegetation plays a key role in regulating the atmospheric dynamics and also ensures the survival of both the humans and animals. Monitoring vegetation productivity is important in assessing threats to environment and to ensure feed and food sustainability to humans and animals. Ali *et al.*, 2013 estimated vegetation productivity using normalized difference vegetation index (NDVI). It is an indicator of photosynthetic activity in a living plant. It has been used as an indicator (proxy) for vegetation vigour and vitality (Reeves *et al.*, 2002).

Droughts are the major climatic conditions which affect vegetation and livelihoods in the ASALs. It is in the dry periods in Magadi when the effects of water and forage shortages are most apparent. Among the effects is the low vegetation quality and quantity. Vegetation productivity during the dry seasons is one of the most limiting factors to pastoral livelihood sustainability in the ASALs (Kazmi *et al.*, 2010). Dry season vegetation and *Prosopis* productivity was established due to the significance of the dry seasons to the pastoral communities and the green *Prosopis* all year round (Kazmi *et al.*, 2010). It has a direct consequence to pastoral livestock production systems. It is, therefore, important to understand the vegetation dynamics during these critical periods (Patel *et al.*, 2012) as it informs decision making for interventions (FAO, 2007). It is also during the dry seasons when *Prosopis* has superior competitive capacities for survival in these areas (Kazmi *et al.*, 2010). It is the period when it is easy to isolate *Prosopis* from the other plants due to its greenness when all the other plants have either shed leaves or dried up.

Vegetation productivity during the dry seasons is one of the most limiting factors to pastoral livelihood sustainability in the ASALs (Agnew *et al.*, 2000). It has a direct consequence to pastoral livestock production systems. It is, therefore, important to understand the vegetation dynamics during these critical periods as it informs decision making for interventions.

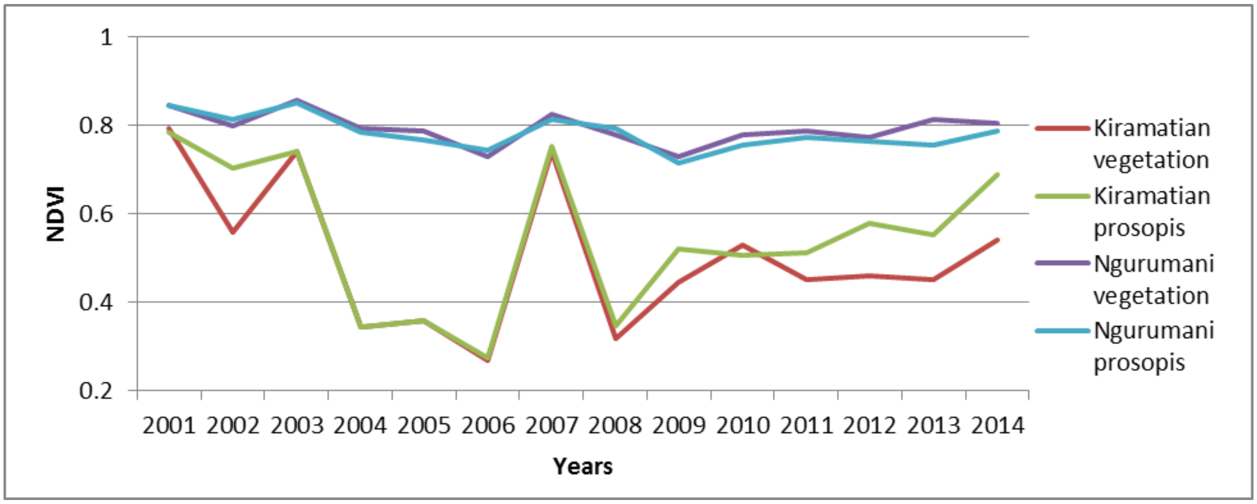
4.4.5. Comparisons of *Prosopis* and other vegetation productivity trends

There were few fluctuations, similar trends and higher values in the NDVI values in the Ngurumani *Prosopis* and other vegetation in both the short and long dry seasons (Fig. 4.5a and Fig. 4.5b). This was because of the higher water endowment in Ngurumani hill slopes for most of the time during the year.

In the Olkiramatian *Prosopis,* the situation was different. The superior competitive advantage of *Prosopis* was evident in the steady increase of NDVI values from year 2008 in both the short and long dry seasons, after a period of similar pattern to that of the other vegetation types (Fig. 4.5a and Fig. 4.5b). However the *Prosopis* NDVI increase in Olkiramatian was most prominent during long dry period, when it was consistently higher than that of the other vegetation and it marched the trends in the water endowed Ngurumani *Prosopis* in 2003 and 2004 (Fig.4.5b). Reasons for these patterns could be due to *Prosopis* superior competitive coping capacities during the dry seasons (de Bie *et al.,* 2011).

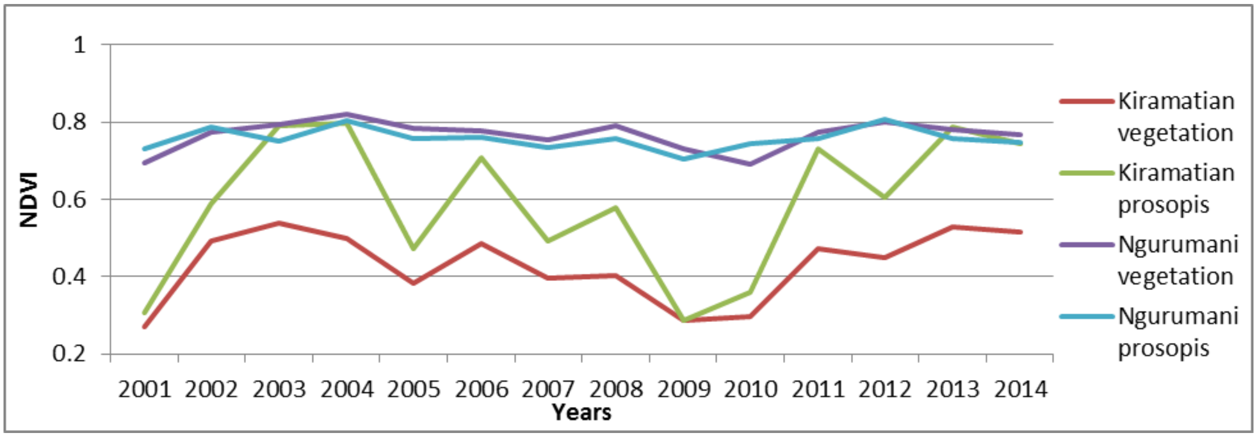
4.4.6. Livestock population trends in Magadi

There was little change (R^2=0.1) in the population trends of goats and sheep (shoats) from 2001 to 2013 (Fig. 4.6). However, there was significant change (decrease) in the cattle numbers (R^2=0.6) during the same period and the population numbers were decreasing (Fig. 4.6). This could be explained partly by the disappearance of the grasslands (GOK- PDNA 2012) and the appearance of the *Prosopis,* among other shrubs, replacing the former grasslands. Goats and sheep are generally browsers, feeding mainly on shrubs. The shoats were also known to browse



Source: Analysis based on MODIS 250m data from Endeleo website (http://endeleo.vgt.vito.be/)

Figure 4.5a: Comparisons of NDVI trends (2001-2014) for the short dry seasons in Olkiramatian location of Magadi Subcounty, Kenya



Source: Analysis based on MODIS 250m data from Endeleo website (http://endeleo.vgt.vito.be/)

Figure 4.5b: Comparisons of NDVI trends (2001-2014) for the long dry seasons in Olkiramatian location of Magadi Subcounty, Kenya

on *Prosopis* (Koech *et al.,* 2010). Cattle mainly feed on grasses, which was on the decline. The opening up and alienation of the Ngurumani dry season grazing areas for irrigated agriculture (Agnew *et al.*, 2000) has also contributed to the decrease of the cattle population.

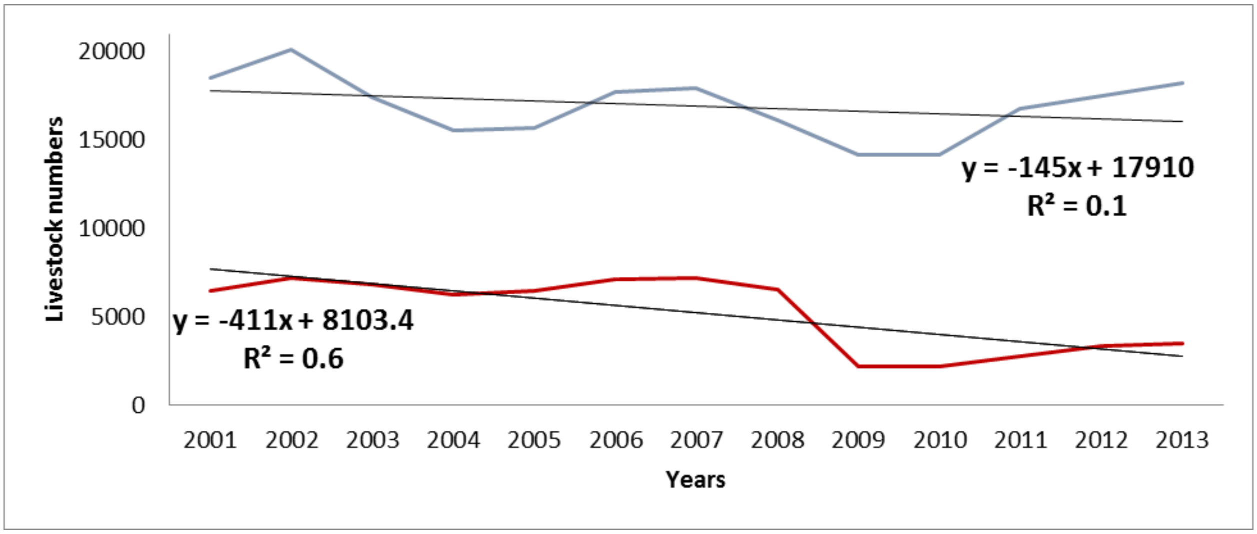
4.4.7. Relationships among rainfall, temperature, Prosopis, other vegetation and livestock trends

Correlation analysis was done to determine the relationship between climate variability, P. *juliflora* spread, vegetation change and livestock population dynamics and it was found that the correlations were significant at the 0.05 confidence level (Table 4.1). Correlation coefficients for *Prosopis* spread against rainfall were -0.4 in Olkiramatian and coefficients for *Prosopis* spread against temperature were 0.3 in Ngurumani and Correlation coefficient for *Prosopis* spread against cattle was –0.4 (Table 4.1). Although the correlation coefficients were low for *Prosopis*, these values could be higher if the period of study was divided into two (from 2001 to 2008 and 2009 to 2004). In the first period (from 2001 to 2008) *Prosopis* biomass was declining and the second period (2009 to 2004) *Prosopis* biomass was on the increase.

4.4.8. Conclusions and recommendations

The study revealed decreasing and variable rainfall amounts and patterns; and an increase in mean annual temperatures in the study area. The vegetation cover was noted to decline especially during the long dry seasons when livestock feed supply was limited and *Prosopis* cover was increasing during the same period. The cattle populations were also on the decline over the 13 year study period while the sheep and goats populations remained largely unchanged.

These trends could be attributed partly to climate variability. With climatic variability expected to continue, it was recommended that viable *Prosopis* utilization options be explored to take advantage of its adaptability to climate variability.



Source data: Magadi Division Livestock Office, (2014)

Figure 4.6: Livestock population trends (2001-2013) in Olkiramatian location of Magadi Subcounty, Kenya

Table 4.1: Summary table of regression results for rainfall (mm), temperature (^{0}C), Prosopis biomass and livestock population trends over time (years) in Olkiramatian location of Magadi sub county, Kenya

Regression statistic	Rainfall (mm)	Temperature (^{0}C)	Prosopis biomass Olkiramatian	Prosopis biomass Ngurumani	Cattle population (No.)	Shoats population (No.)
Intercept	33758	-692	-48	1.45	831773	308085
Coefficients	-16	0.36	0.025	-0.0003	-411	-145
R Square	0.30	0.74	0.44	0.003	0.60	0.106
Standard Error	8	0.064	16	3.9	101	126

Table 4.2: Correlations among rainfall, temperature, *Prosopis*, other vegetation and livestock populations in Olkiramatian location of Magadi Subcounty, Kenya

	Rainfall totals	Average Temperature	Kiramatian vegetation	Kiramatian Prosopis	Ngurumani vegetation	Ngurumani *Prosopis*	Cattle	Shoats
Rainfall totals	1	-.169*	.360**	-.367**	.385**	.227**	.093	.158
		.039	.000	.000	.000	.005	.256	.052
Average Temperature		1	-.219**	.228**	-.375**	-.343**	-.523**	-.319**
			.007	.005	.000	.000	.000	.000
Kiramatian vegetation			1	.856**	.620**	.602**	.073	.244**
				.000	.000	.000	.376	.003
Kiramatian Prosopis				1	.611**	.597**	-.364	.241**
					.000	.000	.400	.003
Ngurumani vegetation					1	.734**	.251**	.314**
						.000	.002	.000
Ngurumani *Prosopis*						1	.337**	.330**
							.000	.000
Cattle							1	.559**
								.000
Shoats								1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

5. CHAPTER 5: SPREAD DYNAMICS OF PROSOPIS JULIFLORA AROUND MAGADI, KENYA

5.1. Abstract

A study was conducted in 2014 to determine the spatial and temporal spread of *Prosopis juliflora* in the Ngurumani hillslopes and Olkiramatian floodplain landscapes around Magadi, Kenya. Changes in the *Prosopis juliflora* biomass was estimated between 2000 and 2013 using the normalized difference vegetation index (NDVI) and net primary productivity (NPP) with a spatial resolution of 250m from MODIS satellites. The NDVI of *Prosopis* in the Olkiramatian floodplain had a lower mean (0.49) and a wider range (0.6), while on the Ngurumani hillslopes NDVI had a mean of 0.78 and a range of 0.3. *Both* NDVI and NPP were positively correlated with the cover of *Prosopis* in both landscape units ($r=0.7$; $P<0.5$; $r=0.9$; $P<0.5$). This suggests that NDVI is a good predictor of NPP in both plains and hillslopes, with more reliability in the floodplains. The annual rate of spread in 2000, 2006 and 2013 was 0.13, 4.76 and 13.09 km^2 respectively in the plains, representing a significant increase during the study period. In the hillslopes, there was minimal change in the rate of spread in 2000, 2006 and 2013 (5.36, 5.37 and 5.29 km^2 respectively). It was concluded that there was more rapid spread of Prosopis in the floodplains than the hillslopes.

Keywords: NDVI, NPP, *Prosopis C*over, spread

5.2. Introduction

Prosopis Juliflora (Sw.) DC (hereafter simply Prosopis) is known as Mesquite in Latin America and Mathenge in Kenya. Prosopis is a fast-growing, thorny, and strongly branching shrub or tree belonging to the family of the Fabaceae (Mimosoideae). Classified as a phreatophyte, its roots require access to the groundwater table. It was introduced for land rehabilitation in Tana River County during the 1970s and 1980s (Choge and Pasiecznik, 2006; Wahome *et al*, 2008). Its adaptation characteristics to climate variability, tolerance to aridity and massive seed production (Andersson *et al.,* 2005), enables it to invade grazing and farm lands in areas of its introduction (Pasiecznik *et al,* 2001; Tewari *et al,* 2000) through ubiquitous seed production: up to 80 kg (up to 2000 seeds) of pods in one season per tree. It is estimated that 2% of Kenya's landmass is now under *Prosopis*; and its pod production potential has been estimated at about 60,000 tonnes per year (Leparmarai *et al.,* 2015; Choge and Pasiecznik, 2006). *Prosopis juliflora* is in IUCN's new list of 100 world's worst invasive alien species, but the invasion in Kenya's drylands has recently attracted national attention and contradictory responses from responsible agencies (Mwangi and Swallow, 2005). It grows well in regions with 100 to 600 mm rainfall with plant heights of 3 to 15 metres, depending on soil type and climate, (Leparmarai *et al.*, 2015).

Communities living in the arid and semi-arid lands (ASAL) have complained about this new and difficult plant to control that has little benefit. In Baringo, for example the local populations went to court in an attempt to force the Government to remove the plant (Maundu *et al.,* 2009; Wahome *et al,* 2008; Pasiecznik *et al*, 2001). Some countries have tried and failed to eradicate it (Choge and Pasiecznik, 2006) but there are viable options for economic use of its products to enable communities benefit and control its spread (Silva, 1986; Pasiecznik *et al,* 2001). Alternative commercial utility lies in quality animal feeds (only the pods as the leaves are not palatable) and carbon trading Koech *et al.,* 2010). However, more precise information on biomass production / or accumulation and carbon sequestration is needed especially for rangelands surrounding waterbodies and wetlands where it is spreading (Felker *et al.,* 1986; Galvin *et al.,* 2004; Geesing *et al.,* 2004). Lack of information on biomass production of *P.*

juliflora has hampered its potential utilization (Wahome *et al*, 2008; Pasiecznik *et al*, 2001). It is, therefore, important to develop *Prosopis*-specific models that can be used to predict spatial and temporal future spread patterns (Kaur *et al.*, 2012; Singh and Bilas, 2011) in the drylands to enhance understanding and exploitation of *Prosopis* productivity and carbon stocks. This will inform strategies to enhance pastoral production, incomes and resilience to climate variability (WISP, 2007; Silva, 1986).

Prosopis juliflora was introduced in Olkiramatian location between 1989 and 1994 and it has been able to tolerate difficult environments including frequent and intensive droughts in the floodplains, alkaline soils, sandy soils and highly degraded areas (Pasiecznik *et al*, 2001). It is always green when most of the other vegetation types have either dried up or shed their leaves to cope with drought. This study was conducted to provide empirical data on the spatial and temporal spread dynamics (Atzberger *et al.*, 2014) of *Prosopis juliflora* in Magadi Division, Kenya to inform about potential future exploitation opportunities. This is therefore a first-time report on *Prosopis* spread in Magadi. The presented data are however only a first glimpse of spread dynamics.

5.3. Materials and methods

5.3.1. The study Area

The study was conducted in Magadi division of Kajiado County, Kenya, that represents about 8% (author’s estimate) of the drylands of Kenya (Fig. 3.1: Study area in Magadi of Kajiado County) infected by P. juliflora.

The study area falls under the inner lowland and lower midland agro-ecological zones, (de Bie *et al.*, 2011). It is sparsely populated except for the agricultural zones of Ngurumani escarpment.

Kajiado County is located in south west of Kenya, bordering Tanzania to the south and Narok County to the west. It is situated between 1°40’S, 36°E, 2°S, 36°15’E (Fig. 3.1).

The area is predominantly pastoral land inhabited by the Maasai ethnic community whose main source of livelihood is nomadic pastoralism characterised by extensive livestock production on communally owned land. The community traditionally practiced crop cultivation to complement food and income from livestock and livestock products. In the recent past, however, crop farming by the Maasai and immigrant farming communities has increased especially in areas receiving enough rainfall to permit rainfed agriculture and riparian areas with opportunities for irrigation.

Magadi Division has a bimodal rainfall pattern (January to February being the short dry season, March to May being the long rainy season, June to September being the long dry season and October to December being the short rainy season) with a an annual total of 460mm and a mean of 50mm, mean altitude of 600m, mean temperatures of 32 °C and generally alkaline soils which are mainly sandy loam and silt clay (Agnew *et al.*, 2000). The climate is hot and arid to semi-arid and the vegetation is mainly sparse, open bushland dominated by the *Acacia tortilis, Ficus sycomorus, Salvadora persicca* and *Vachellia* species (Agnew *et al.*, 2000). The understory consists of shrubs such as *Grewia spp., Boscia* and *Trichilia roka,* and grass species that include *Echinochloa haploclada* (Agnew *et al.*, 2000). *Prosopis* invasion is evident in Olkiramatian, Entasopia and Ngurumani sublocations since the year 2000.

Prosopis is particularly found in Olkiramatian, Ngurumani, Ol chorro Olepo and Entasopia sub-locations of Olkiramatian location in Magadi division. These are the original sites where *Prosopis* was introduced by the Ministry of Forestry in in 1994 (local key informants). The species later spread to other areas in Magadi namely Musenge, Lorngosua sublocations of

Olkiramatian location, Kamukuru and Kora sublocations of Ol Donyo-Nyoike location and Lenkobea sublocation of Shompole location. These are low-lying floodplains areas with high water table and alkaline soils, the perfect prerequisites for *Prosopis* establishment. This study was conducted in Olkiramatian, Ngurumani, Ol chorro Olepo and Entasopia sub-locations of Olkiramatian location, where there are well established P. *juliflora* stands ranging from dense, moderate and sparse clusters represented in theflood plains and hill slopes landscapes.

5.3.2. *Prosopis* spread dynamics assessment using GIS and remote sensing tools

Geographical information systems (GIS) and remote sensing tools were used in this study. Satellite remote sensing provided vegetation data, based on major species composition, canopy density and site conditions. Remote sensing studies have shown that the normalised difference vegetation index (NDVI) can be related directly to vegetation amount (above ground biomass) and net primary productivity (NPP) (Tucker, 1979). Normalized Difference Vegetation Index (NDVI) is an expression of the photosynthetic activity of green plants. It is expressed as:

NDVI = (NIR - Red) / (NIR + Red)…………………………Equation 5.1,

where NIR (near infra read) and Red are the visible bands of the electromagnetic wavelength. It is expressed in values in the range of -1 to +1 (Tucker, 1979)

Moderate-resolution Imaging Spectroradiometer (MODIS), a NASA satellite (Zhao and Running. (2010); https://lpdaac.usgs.gov/products/modis_products_table/mod17a3), has been operational since 1999. It has TERRA and AQUA sensors onboard and these instruments are designed to provide daily, weekly and bi-weekly vegetation data, from raw images to value-added products (NDVI and NPP) (Huete *et al.*, 2002) through modelling. They have spectral bands ranging from 250m to 1km resolutions.

Monteith model (Monteith, 1972; Atzberger *et al.*, 2014) has been used to estimate biomass production using the following equation:

NPP=APAR .LUE…………………………………….…………Equation 5.2:

Where: NPP is the net primary production; APAR is the Absorbed Photo-synthetically Active Radiation and LUE is the Light Use Efficiency factor.

Biomass has also been estimated for agroforestry systems in eastern Kenya (Kinama *et al.*, 2011) and LUEs for these areas were established.

Land cover, land use and soil attributes are geographical features which are expressions of human activities and form a reference base for applications ranging from forest and range monitoring to biodiversity, climate change and desertification control . These attributes together with the NDVI and NPP products were used to identify and monitor of spread patterns and trends of *Prosopis* in this study.

5.3.3. Sampling design

A baseline survey was used to delineate sampling sites and identify local key informants, who are knowledgeable about *Prosopis juliflora* invasion in Magadi division. The study area was divided into two landscape categories based on land terrain namely, hillslopes and floodplains. In each of these categories, three classes of *Prosopis* densities were purposefully selected based on ground cover. These were: - sparse density (less than 30% *Prosopis*); moderate density (50-70% *Prosopis)* and high density stands (greater than 70% *Prosopis*). In each of these *Prosopis* density classes, 4 plots of 30m by 30m were randomly selected. A total of twelve plots in each of the two landscape categories were randomly selected, fenced off and GPS points recorded.

5.3.4. Data collection and analysis

Vegetation data for the period 2000 – 2014 from MODIS satellite images were analysed to determine the spread and biomass production of *Prosopis juliflora* in the study area. The normalised difference vegetation index (NDVI) and net primary productivity (NPP) derived from MODIS images with spatial resolution of 250m (Huete *et al.,* 2002) were used to establish the spread and quantities of *P. juliflora.* Land use, land cover and soil data, GPS data and GIS databases were used to identify areas with the suitability characteristics for *Prosopis* to thrive and the spatial and temporal spread patterns of *Prosopis* analysis. They were also used to validate the spatial locations of *Prosopis*. The NDVI was also used to identify the vegetation types which are photosynthetically active during the drought periods. These vegetation types will most likely be *Prosopis*.

5.3.5. Interpretation of NDVI and NPP values

To identify the 'Vegetation health and density', the NDVI was used. The NDVI values in the NDVI images have physical values ranging between -1.0 and 1.0, where higher values indicate denser and healthier (higher green density) vegetation. This index is unitless (Atzberger *et al.,* 2011; Running, 1986; Grace *et al.,* 2006; http://endeleo.vgt.vito.be/).

NDVI = (NIR - Red) / (NIR + Red)…………………….……Equation 5.3,

where NIR (near infra read) and Red are the visible bands of the electromagnetic wavelength.

NDVI values of 0.1 and below typically correspond to areas with little to no vegetation (rocks, ice, and desert). Moderate values (around 0.2 and 0.3) correspond to shrub and grasslands and high values (0.5 and above) typically correspond to dense vegetation like rainforests (http://endeleo.vgt.vito.be/).

To measure the vegetation growth rate, the net primary productivity (NPP) was used. It is calculated as cumulative dry matter per hectare per month (kg/ha/month)

NPP=APAR .LUE:……………………………………………..….Equation 5.4,

where NPP is the net primary production; APAR is the Absorbed Photo-synthetically Active Radiation and LUE is the Light Use Efficiency factor

NPP reflects only the above-ground biomass and as such NPP should be interpreted as indicative for "potential" production. Higher NPP values indicate a higher growth rate, so more production of dry matter biomass. (http://endeleo.vgt.vito.be/).

The area occupied by *Prosopis* clusters was calculated from the digitized from the participatory mapped *Prosopis* locations and the GPS points of the randomly selected field 30x30m *Prosopis* plots. The *Prosopis* NDVI values for the years 2000, 2006 and 2013 was extracted from the general vegetation NDVI values in the MODIS 250m images and used in determining the area occupied by *Prosopis* ArcGIS software was used in extracting the *Prosopis* NDVI values for both the short and long dry seasons.

Regression analysis for *Prosopis* biomass (NPP) trends against time in Olkiramatian flood plains and Ngurumani hillsploes of Magadi sub county, Kenya were done

To determine relationships between trends in *Prosopis* and other vegetation cover, correlation analysis was used to assess the strength and direction of relationships between the NDVI and NPP and the locations of *P. juliflora* stands on the ground. Correlation analysis was used to determine the relationships between the NDVI and NPP products and the ground *Prosopis* locations (*Prosopis* GPS points). Range, mean, standard error, standard deviation and variance) were analysed using SPSS ver.2010.

5.4. Results and discussions

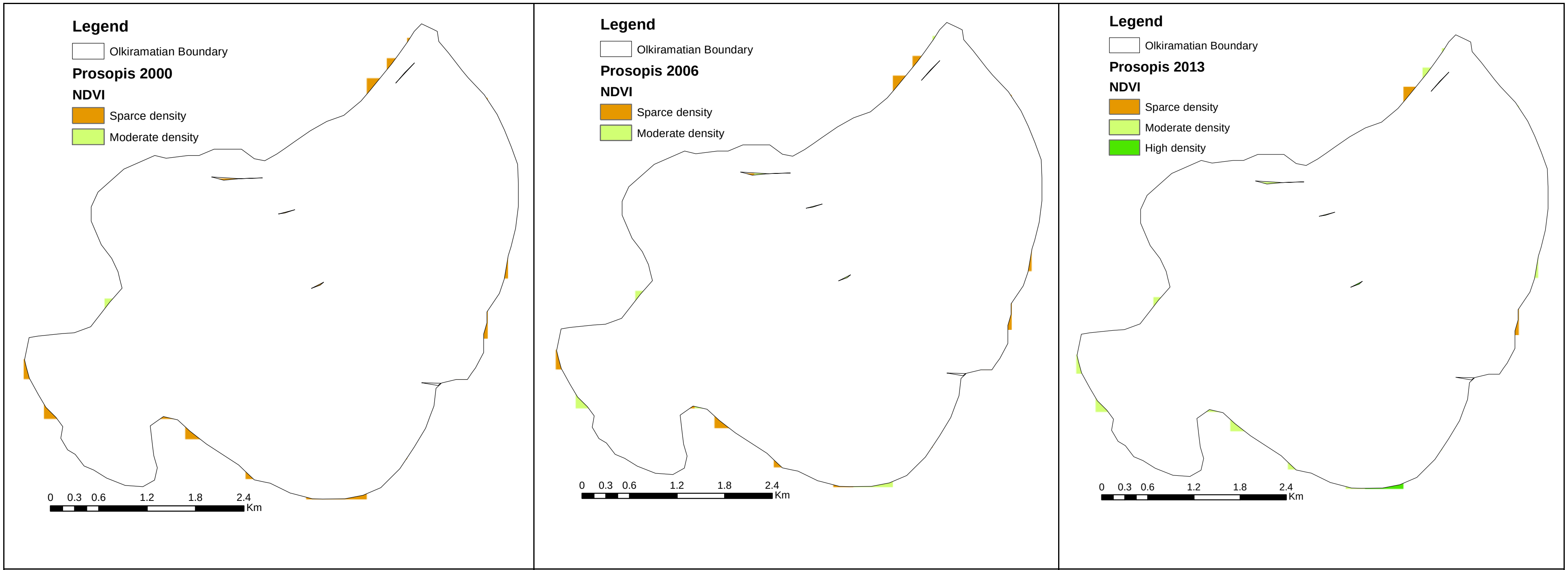
Prosopis NDVI in Olkiramatian had a lower mean (0.5) and a higher range (0.6) compared to *Prosopis* NDVI in Ngurumani (mean of 0.7 and range of 0.3). The two landscapes of P. *juliflora* invasion in Olkiramatian floodplains and Ngurumani hillslopes as identified with the assistance of the local key informants and the delineated sampling sites represented by GPS points were mapped and overlaid with the field *Prosopis* samples plots. (Fig.5.1 and Fig. 5.2). The Olkiramatian floodplains were populated more by the sparse and moderate *Prosopis* densities compared to Ngurumani hillslopes with more of the high density *Prosopis* stands.

Spatial trends of *Prosopis* spread from the year 2000 to 2013 in the drier Olkiramatian plains and the wetter Ngurumani hillslopes were analysed (Fig. 5.1 and Fig. 5.2). In 2000, the *Prosopis* NDVI in Olkiramatian plains was in poor and low quantities (Fig. 5.1). It was still establishing itself and developing the competitive and adaptive features (Getachew *et al.,* 2012) for survival in the drylands. It was being suppressed by the other vegetation types and most of it was in poor state as seen in Figure. 5.1. Six years later, in 2006, Prosopis NDVI was increasingly getting in the normal state (Fig. 514), which was an indication that it was exerting (manifesting) its superior coping and survival rates in drylands and gaining ground over the other plants in terms of survival (Agnew *et al.,* 2000). *Prosopis* was gaining ground, exerting its competitive edge over the other vegetation types and exerting (manifesting) its superior coping and survival rates in drylands (Choge and Pasiecznik, 2006; Wahome *et al.,* 2008).

In 2013, *Prosopis* NDVI was dominantly in normal and getting into the good NDVI range (Fig. 5.1). It outcompeted the other vegetation types and its strong dryland survival and coping strategies were evident (Getachew *et al.,* 2012; Pasiecznik *et al.,* 2001).

Overall, the green *Prosopis* vegetation, which was represented by NDVI, was low but in steady increase during the study period (2000-2014) in Olkiramatian plains. Olkiramatian plains exhibit more aridity conditions (average temperatures of 37^0C and 250mm annual rainfall) (Agnew *et al.,* 2000). This suggested that *Prosopis* had a higher competitive edge over the other vegetation types for survival and coping rates in the drylands (Muturi *et al.,* 2010). In the Ngurumani hillslopes, the scenario was different from that of Olkiramatian floodplains. The *Prosopis* NDVI values were high in 2000, 2006 and 2013 in Ngurumani hillslopes (Fig. 5.2). There were minimal NDVI fluctuations and this could be explained by the relatively higher annual rainfall amounts (587mm) and lower average temperatures (33^0C) (Galvin *et al.,* 2004; Agnew *et al.,* 2000). These are favourable conditions for a majority of dryland vegetation types to compete for survival. This suggested that *Prosopis* was not able to outcompete the other vegetation types but remained in good condition throughout the study period (2000-2014) (Vrieling *et al.,* 2014; Mwangi and Swallow, 2005).

Similar studies elsewhere (de Bie *et al.,* 2011) showed that single monoculture crop fields could be monitored for yield predictions using MODIS NDVI models. Meroni *et al.,* (2014) monitoring "reverse phenology" (shedding leaves at the peak of the rainy season, while being in full leaf throughout the dry season) of *Faidherbia albida (syn Acacia albida D.*) using satellite images found out that MODIS NDVI was a reliable estimator of biomass production. The two studies managed to isolate the single tree species for monitoring and estimation of biomass production using NDVI (Vrieling *et al.,* 2014).



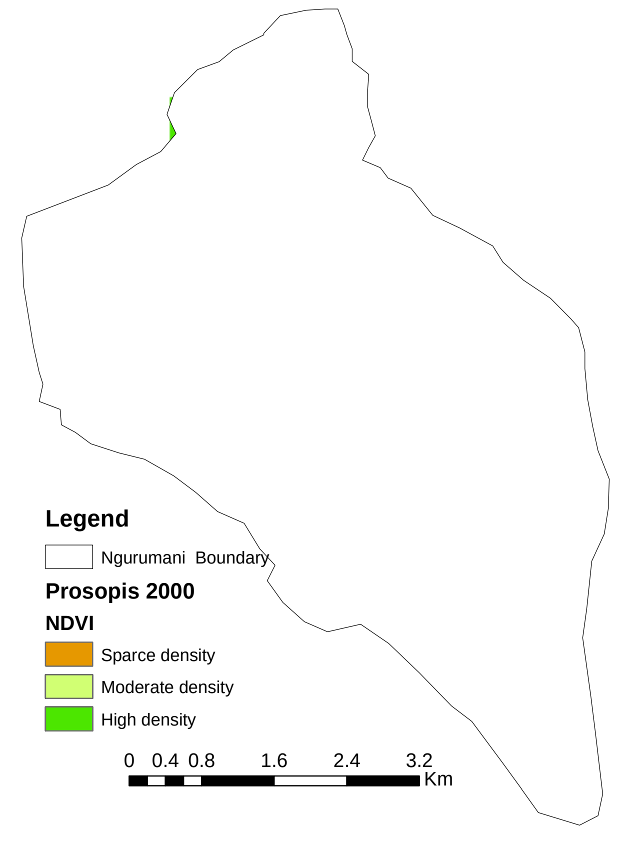
Prosopis spatial spread in Olkiramatian plains in 2000

Prosopis spatial spread in Olkiramatian plains in 2006

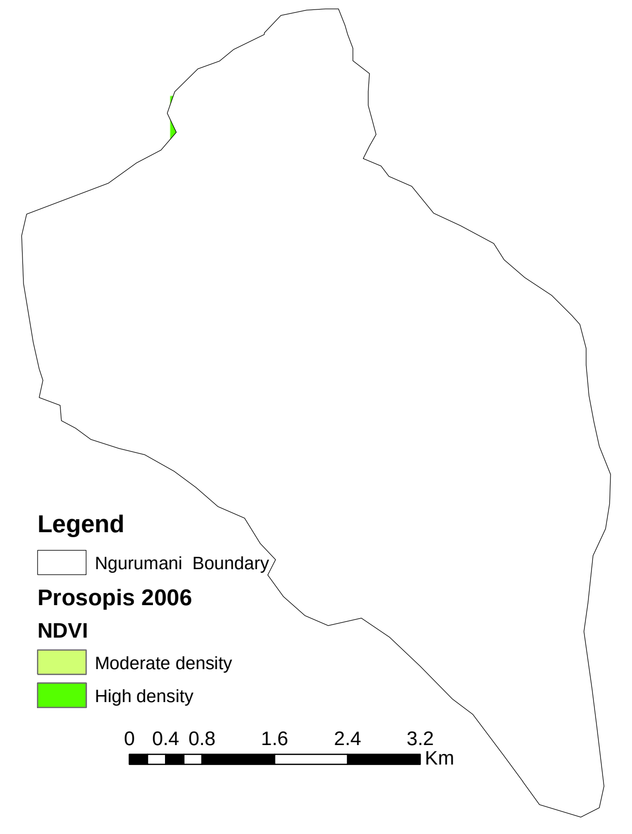
Prosopis spatial spread in Olkiramatian plains in 2013

Source: Analysis based on NDVI data from Endeleo website (http://endeleo.vgt.vito.be)

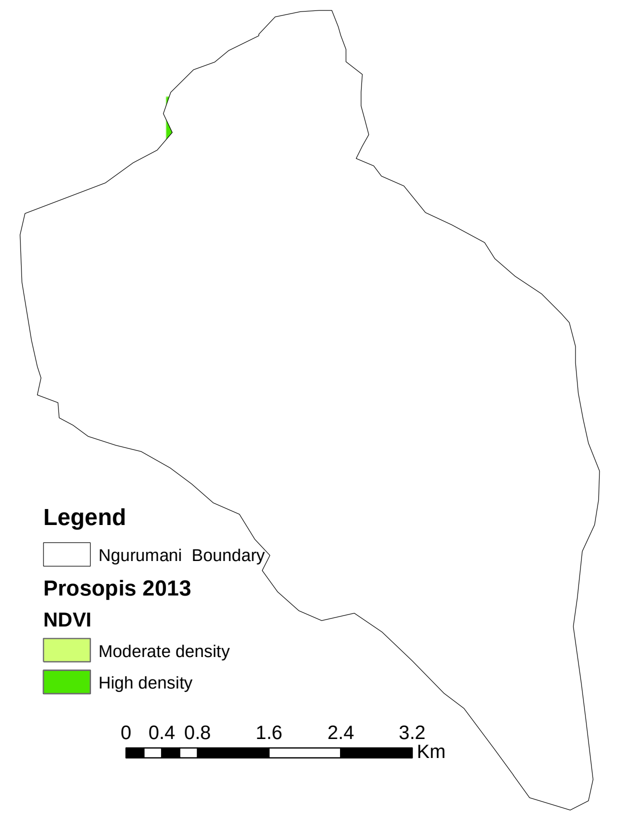
Figure 5.1. *Prosopis* cover change from 2000 through 2006 to 2013 in Olkiramatian location of Magadi Subcounty, Kenya



Prosopis spatial spread in Ngurumani hillslopes plains in 2000



Prosopis spatial spread in Ngurumani hillslopes in 2006



Prosopis spatial spread in Ngurumani hillslopes in 2013

Source: Analysis based on NDVI data from Endeleo website (http://endeleo.vgt.vito.be)

Figure: 5.2: Spatial *Prosopis* spread from 2000, through 2006 to 2013 in Ngurumani hillslopes in Olkiramatian location of Magadi Subcounty, Kenya

5.4.1. Temporal spread of *Prosopis juliflora* in plains and hillslopes landscapes

The area occupied by *Prosopis* increased steadily from 2006 to 2013 (Fig 5.3) in the Olkiramatian floodplains. This could be attributed to the superior competitive qualities of *Prosopis*, depressed rainfall amounts (Fig. 5.4) and the tolerant behavour of the *Prosopis juliflora* to saline soils (Shiferaw *et al.,* 2004; Pasiecznik *et al.*, 2001). In Ngurumani hillslopes, the area occupied by Prosopis remained relatively the same from 2006 to 2013 (Fig 5.3).This was attributed the higher rainfall regimes witnessed in Ngurumani. The higher water availability in Ngurumani made *Prosopis* less competitive in this area, hence the slow rate of spread.

Less fluctuating trends and high values in *Prosopis* NDVI were witnessed in Ngurumani hill slopes (Fig 5.3), which receives moderately higher rainfall amounts than the Olkiramatian plains (Agnew *et al.,* 2000) is the traditional dry season grazing area of the local Maasai community. It has numerous natural springs flowing throughout the year (Agnew *et al.,* 2000). In the early 2000s' much of its woodlands and bushlands were opened up for irrigated agriculture (Agnew *et al.*, 2000)].

The combination of the opened spaces, saline soils, Ewaso Ngiro riverine ecosystem and the severe droughts of the late 2000s' encouraged *Prosopis* colonization (Mwangi and Swallow, 2005; Agnew *et al.*, 2000; Robinson *et al.*, 2008). Although *Prosopis* is colonizing the area at a faster rate (average of 6km^2/year in Olkiramatian plains and 5.3km^2 in Ngurumani hillslopes compared to the other vegetation types), it has not reached the stage where it can competitively suppress the other vegetation types. This is due to the availability of relatively adequate water sources to enable other plants to compete favorably (Yoda *et al.*, 2012; Rettberg and Müller-Mahn, 2012).

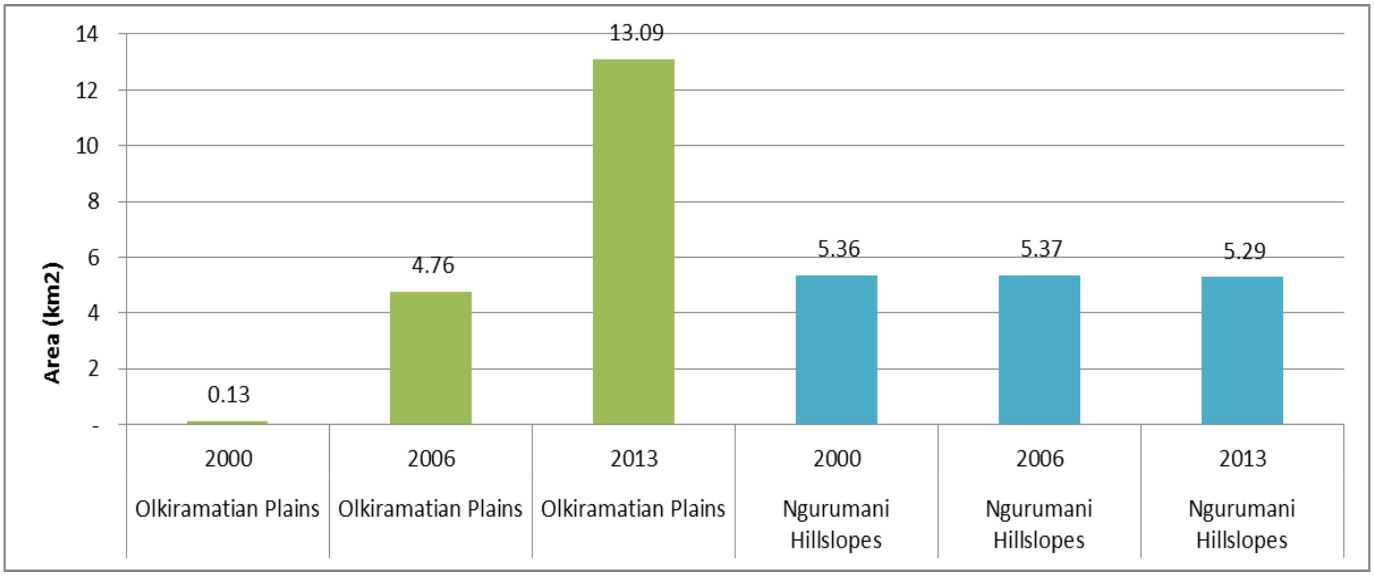
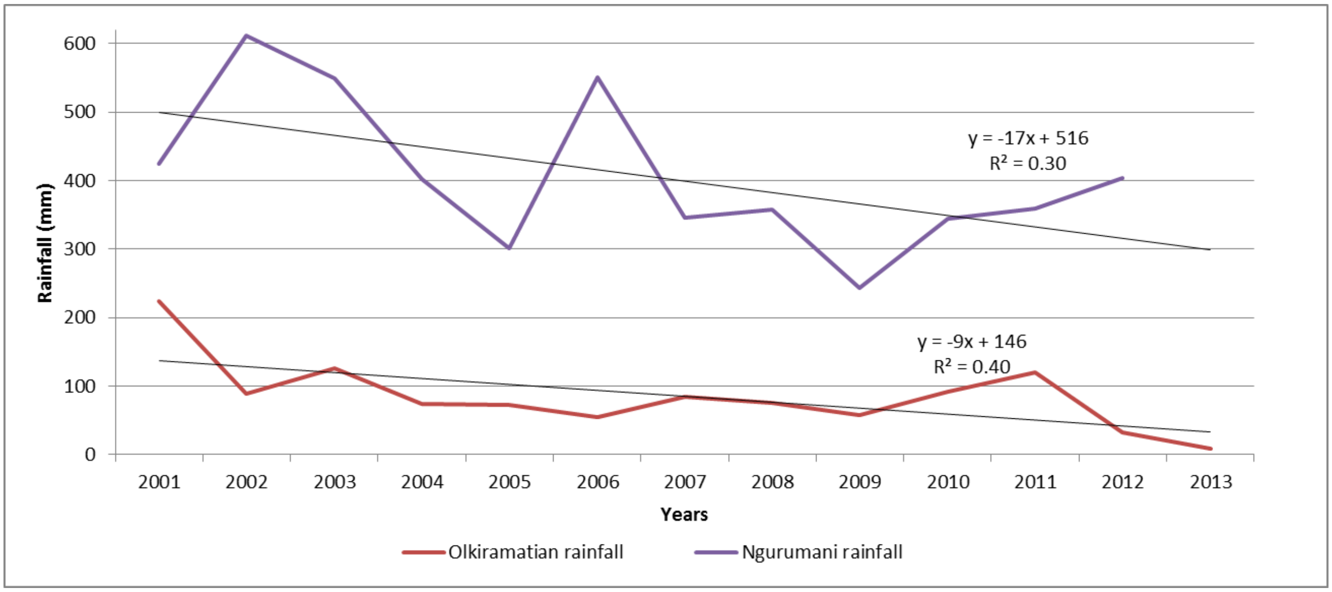


Figure 5.3: Rate (km^2/year) of *Prosopis* spread (2000 to 2013) in Olkiramatian plains and Ngurumani hillslopes of Magadi Subcounty, Kenya.



Source: MSC Meteorological Department, 2014

Figure 5.4: Annual rainfall (mm), trends (2001 - 2013) in Olkiramatian plains and Ngurumani hillslopes of Magadi Subcounty, Kenya

The high NDVI values (greater than 0.7) (Fig 5.3) during the dry seasons is an indication that there are favorable conditions for *Prosopis* to thrive, notably good supply of water.

Comparing *Prosopis* NDVI trends in Olkiramatian plains and Ngurumani hillslopes revealed a more stable trend in Ngurumani and fluctuating trend in Olkiramatian (Fig 5.3). In Olkiramatian, the trend followed the highly variable rainfall patterns, with a heavy dip in the period 2007-2009, when there was a severe drought in the area. In Ngurumani, however, the trend is less fluctuating, a reflection of the higher and stable annual rainfall (water) availability in the area ((average temperatures of 37^0C and 250mm annual rainfall in Olkiramatian and annual rainfall amounts (587mm) and lower average temperatures (33^0C) in Ngurumani))

5.4.2. *Prosopis juliflora* cover trends using time-series net primary productivity

Net primary productivity (NPP) trends revealed similar patterns to the NDVI in Olkiramatian plains but slightly different in Ngurumani hillslopes (Fig. 5.5). The initial years of establishment (2000-2008) *Prosopis* productivity was not very competitive and on downward trend, but from 2009 to 2013, *Prosopis* productivity became competitive on an upward trend. Ngurumani *Prosopis* NPP were consistently higher (between 70kg/ha to 140kg/ha) compared to Olkiramatian *Prosopis* NPP (between 15kg/ha to 50kg/ha) (Fig. 5.5). This is attributed to the higher rainfall and lower temperatures (587mm) and lower average temperatures (33^0C) recorded in Ngurumani as compared to Olkiramatian (average temperatures of 37^0C and 250mm annual rainfall) over the study period. The effects of the 2007-2009 drought was more evident in the NPP trends (Fig. 5.5), which followed the drought patterns than the NDVI trends in Ngurumani hillslopes, which seemed to withstand the fluctuations associated with the drought patterns).

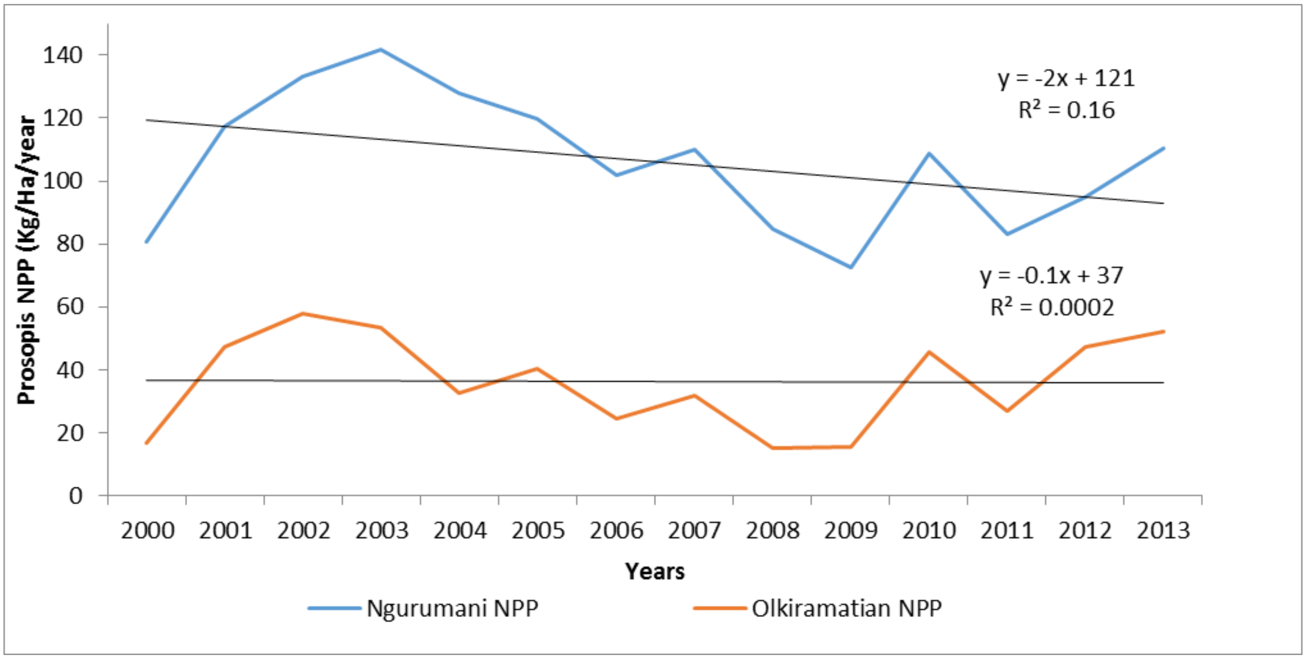
Studies elsewhere (Vrieling *et al.,* 2014; Kale *et al.,* 2002; Pareta and Pareta, 2011) showed that biomass and productivity could be monitored and estimated using aerospace data and Geographic Information Systems. Similarly, satellite remote sensing techniques have been successfully used to determine forest carbon stocks and calculated carbon sequestration (Roy and Ravan, 1996; Vrieling *et al.*, 2014).

Table 5.1: Summary of regression results for *Prosopis* NPP trends in Olkiramatian plains and Ngurumani hillslopes of Magadi subcounty, Kenya

Regression statistic	*Prosopis* NPP - Olkiramatian	*Prosopis* NPP - Ngurumani
Intercept	225	1581
Coefficients	-0.09	-0.7
R Square	0.00015	0.016
Standard Error	0.56	0.44

5.4.3. Correlations of Olkiramatian and Ngurumani *Prosopis* NDVI and NPP over time

Pearson's correlation coefficients were computed to establish linear associations between NDVI and NPP both in Olkiramatian and Ngurumani landscapes (Table 5.1). Olkiramatian *Prosopis* NDVI was strongly correlated with Olkiramatian *Prosopis* NPP with a correlation coefficient of 0.9 at P<0.5. Ngurumani *Prosopis* NDVI was also positively correlated with Ngurumani *Prosopis* NPP with a correlation coefficient of 0.7 at P<0.5. NDVI is a good predictor of NPP in both Olkiramatian plains and Ngurumani hillslopes, but with more reliability in the Olkiramatian plains. The competiveness of other vegetation species in Ngurumani as a result of higher water availability, suppressed the *Prosopis* NPP making it either remain static in growth rate or record a slight decrease.



Source: Analysis based on MDP data from Endeleo website (http://endeleo.vgt.vito.be)

Figure: 5.5 *Prosopis* NPP trends (2000-2013) in Olkiramatian plains and Ngurumani hillslopes of Magadi Subcounty, Kenya.

Table 5.2: Correlations between *Prosopis* NDVI and NPP in the Olkiramatian plains and Ngurumani hillslopes, Magadi Subcounty, Kenya.

		Olkiramatian *Prosopis* NDVI	Ngurumani *Prosopis* NDVI	Olkiramatian *Prosopis* NPP (kg)	Ngurumani *Prosopis* NPP (kg)
Olkiramatian *Prosopis* NDVI	Pearson Correlation	1	0.610**	0.903**	0.687**
Ngurumani *Prosopis* NDVI	Pearson Correlation		1	0.586**	0.714**
Olkiramatian *Prosopis* NPP (kg)	Pearson Correlation			1	0.752**
Ngurumani *Prosopis* NPP (kg)	Pearson Correlation				1

**. Correlation is significant at the 0.01 level (2-tailed).

5.5. Conclusions and recommendations

The study established that the spatial and temporal spread of *Prosopis Juliflora* above ground biomass production could be determined using satellite image derived normalized difference vegetation index (NDVI) and net primary productivity (NPP) data. It suggested that the rate of spread was depended on landscape and climatic conditions. The level of predictions of the spread of above ground biomass production differed from one place to another (Olkiramatian *Prosopis* NDVI and NPP with a correlation coefficient of 0.9 at $P<0.5$ and Ngurumani *Prosopis* NDVI and NPP with a correlation coefficient of 0.7 at $P<0.5$. NDVI)

It was recommended that further studies be conducted to find out why differences existed in the predictions of the *Prosopis* productivity (NPP) using NDVI in different areas.

6. CHAPTER 6: ESTIMATING ABOVE-GROUND BIOMASS AND CARBON STOCKS OF *PROSOPIS JULIFLORA* USING ALLOMETRIC EQUATIONS IN DRYLANDS OF MAGADI, KENYA

6.1. Abstract

Above-ground biomass and carbon stocks of *Prosopis juliflora* were estimated using allometric equations in floodplains and hillslopes landscapes of the drylands of Magadi in Kajiado, Kenya. Three hundred and twenty (320) *Prosopis* trees were sampled in 32 sample plots, out of which one hundred and twenty eight (128) were randomly selected and used for the development of the allometric equations. Basal diameter, diameter at breast height, crown width and tree heights were measured; and fresh weights for the 128 trees taken for the development of *Prosopis* biomass prediction models. Cubic curvilinear and power models yielded better results than linear models in biomass prediction, with basal diameter being more reliable than diameter at breast height, crown width and height. Cubic curvilinear and power models for biomass prediction returned the better R^2 values (0.82 and 0.98) for single and multistemmed *Prosopis* trees respectively. Validation of models revealed significant correlation between predicted and measured tree biomass, suggesting effectiveness of the models in biomass predictions. The dense and managed plots in the hilllslopes had the highest *Prosopis* biomass (44.13 tons/ha) followed by dense and unmanaged plots (43.68 tons/ha). The dense and unmanaged plots of the floodplains had lower estimates (34.15tons/ha) followed by dense and managed (28.01 tons/ha). The moderately and sparsely dense plots in both landscapes recorded lower biomass (18.75 and 3.47tons/ha in hillslopes and 12.72 and 5.09 tons/ha in floodplains respectively). The effects of management were evident in the hillslopes but there were no effects of management in the floodplains. There was growth in the *Prosopis* biomass trends in the dense and unmanaged

Prosopis clusters, but there was no change of in the moderately dense and the sparsely dense clusters during the period of study.

Keywords: *Prosopis*, allometric equations, Biomass, Carbon stocks

6.2. Introduction

Introduced in Kenya for land rehabilitation during the 1970s and 1980s (Choge and Pasiecznik, 2006; Wahome *et al.*, 2008), *Prosopis juliflora* has become invasive through its superior aridity adaptive qualities and ubiquitous seed production. It is a threat to productivity of the drylands due to its invasive nature but on the flip side it offers opportunity for the dryland communities to benefit from carbon credit trade, but there are barriers of initiating carbon credit schemes in the drylands, chief of them is methodological constraints. It is estimated that 2% of Kenya's landmass is now covered by *Prosopis* whose pod production potential has been estimated at about 60,000 tons per year (Choge and Pasiecznik, 2006).

Prosopis trees account for a significant amount of plant biomass and consequently, sequestered carbon worldwide. However, most of the previous studies on plant biomass estimation have focused on species from humid areas with little recognition of those adapted to dry environments. Tree species in arid and semi-arid zones are not currently considered when calculating carbon balances. There is yet an undiscovered value of *Prosopis* in the emerging global market for 'carbon credits'.

Plant biomass is the total amount of live material in a plant that includes water and other chemicals (Hoen and Solberg 1994; Zianis, and Mecuccini, 2004). Carbon is an equivalent of charcoal from a tree when all the water is evaporated and it has been estimated at 50% of plant biomass (Losi *et al.*, 2003; IPCC, 2007; IPCC, 2004). Modest improvements in *Prosopis* silvicutural management can raise biomass by as much as 0.5 tons C/ha/year in the drylands (Reid *et al.,* 2004; Galvin *et al.,* 2004). This is important since in the moisture stressed and degraded soils of the Kenya's rangelands, *P. juliflora* contributes an increasingly significant proportion of sequestered carbon (Steinfeld *et al.,* 2006) with the potential of offering pastoral communities an opportunity to benefit from *Prosopis* based carbon credit trade–off schemes.

Biomass has been estimated by ground physical measurements, otherwise known as allometric equations (Roy and Ravan, 1996), which are unique to particular tree species (Chave *et al.,* 2004*)*. In the drylands, the methods are hampered in part by inadequate and underdeveloped methods of accounting for carbon stocks (Galvin *et al.,* 2004) and highly variable canopy cover among sites and species (Felker *et al.,* 1990; Geesing *et al.*, 1999).

The few allometric equations developed for *Prosopis* biomass estimation (Muturi *et al.,* 2011; Singh G. and Bilas Singh, 2011), cannot be easily replicated and are limited in their application and scaling-up potential (McMurtry *et al.,* 2006; Tennigkeit and Wilkes, 2008).There is need to build consensus around the more reliable parameter to use between basal diameter (BD) and diameter at breast height (DBH) and how to handle the multistemmed nature of *Prosopis* trees in estimating *Prosopis* biomass and carbon stocks (Sarmiento *et al.,* 2005; Montero and Montagnini, 2006; Redondo, 2007). This will contribute to the increased accuracy of the estimated above ground biomass (Chave *et al.,* 2004). This paper reports on the determination of an equation that enhances the accuracy of estimating *P. juliflora* AGB production and carbon stocks to model potential for trading in carbon credits.

6.3. Materials and methods

6.3.1. The study Area

The study was conducted in Olkiramatian location of Magadi division - Kajiado County. The area is located in south west of Kenya, bordering Tanzania to the south and Narok County to the west. It is situated at altitude of 600m within lat/long. – 1°40’S, 36°E, 2°S, 36°15’E (Fig. 3.1), under the inner lowland and lower midland agro-ecological zones (Jatzold and Schmidt, 1983). It has a bimodal rainfall pattern with a an annual total of 460mm and a mean of 50mm, mean temperatures of 32 °C. The soil texture is very clay, clay and loam, with occasional sand. The clay types are montmorillonitic, kaolinitic and interstratified clay (Kenya soil survey, 1997). The landforms are composed of plains, plateaus, low gradient foot slopes, medium gradient hills and occasional high gradient hills (Gregorio and Latham, 2002). The slopes range from flat and wet slopes, gently undulating, rolling and steep slopes. The vegetation is sparse, open bushland, with increasing presence of *Prosopis* (Gregorio and Latham, 2002).

Prosopis spread in Magadi division is mainly found in Olkiramatian location and the study is mainly concentrated in Ngurumani, Olchorro Olepo and Entasopia sublocations. These are the original sites where *Prosopis* was originally introduced. There are well established *Prosopis* stands, with adequate dense, moderate and sparse *Prosopis* clusters. Floodplains and hillslopes landscapes are well represented in these areas.

The study sites were located in the Ngurumani hillslopes in Ngurumani and Entasopia sublocations (Fig. 3.1) and Olkiramatian floodplains in Olkiramatian sublocation (Fig. 3.1). These are the areas invaded by *Prosopis* with well-established *Prosopis* stands in the dense, moderate and sparse clusters.

The Olkiramatian floodplains receive 400mm of rainfall annually, average temperatures of 35^0C and vegetation cover of mainly shrubs, *Prosopis* and bare land. The Ngurumani hillslopes receives 600mm of rainfall annually with mean temperatures of 28^0C and vegetation dominated by bushland, *Prosopis* and irrigated crop fields.

6.3.2. Sampling design and delineating the *Prosopis* density sites

Two (2) *Prosopis* landscape strata of hillslopes and floodplains were selected purposively. Within each landscape, three (3) sites containing sparse (less than 30%) *Prosopis* density, moderate *Prosopis* density (50-70%) and high *Prosopis* density (greater than 70%) were identified purposefully. The density was validated through mapping (delineation) of areas occupied by *Prosopis* using satellite images (MODIS (250m) derived NDVI), land use & land cover and GPS data. For each site, a grid of plots ($30m^2$) was laid out on topo maps. Each plot in the grid was allocated a unique number to enable randomisation.

Each site had four (4) random plots of 30mx30m randomly selected and fenced off except for the high density site, where an additional four plots were selected and managed (pruning and 5m spacing between the *Prosopis* trees). The total number of plots in the whole study area of both landscapes was (2*(4+4+4+4)) = 32

Using participatory resource mapping approach involving the local communities, the study sites were stratified into hillslopes and floodplains, which were further categorized depending on the density of *Prosopis* stands into sparse, moderate and dense *Prosopis* sites. The mapping was done on the area topomap sheet with a scale of 1: 50,000. The identified *Prosopis* strata and sites was then be digitised in GIS software (ArcGIS) to create a GIS shapefiles of *Prosopis* density strata and sties.

In order to randomly select the sampling plots for data collection, the digitized *Prosopis* density shapefiles were then partitioned into $30m^2$ grids and each grid assigned a unique number. MS Excel software was used to generate four (4) random numbers from the unique numbers in each of the four *Prosopis* density sites. The random numbers generated were used as the identifiers of the randomly sampled plots. The selected plots were then identified on the ground using GPS and fenced off to prevent interference from livestock, wildlife and humans and all the field observations taken on them.

In the dense *Prosopis* sites, two (2) $30m^2$ plots were randomly selected and demarcated side by side. One of the two plots had management practices applied (pruning and spacing) and the other plot was left in the natural state as a control to enable comparison of the measured attributes.

6.3.3. Selection and management of *Prosopis* plots

Thirty two (32) plots were randomly selected in each of the two purposefully identified *Prosopis* landscapes of Ngurumani hillslopes and Olkiramatian plains. Four (4) plots were managed and twenty eight (28) were left in the natural state (unmanaged). The managed plots were placed adjacent to the unmanaged plots in the dense sites and demarcated as such. The management involved pruning (2-3 stems per plant) and thinning to space (5m apart) of the naturally occurring trees. Any vegetation undergrowth and re-growth was regularly removed in the managed plots.

The *Prosopis* plants (above 3m in height and producing pods) in each observation plot were identified and counted. Ten (10) *Prosopis* shrubs and trees in each plot were randomly selected (sampled) and basal diameter (m), breast height diameter (m), tree height (m) and crown diameter (m) measurements taken once every month for both managed and unmanaged plots.

Field data collection in the two *Prosopis* landscapes (Ngurumani hillslopes and Olkiramatian floodplains) was done once a month for ten (10) months in each of the 32 plots. In the managed plots, stems were thinned and pruned (2-3 stems per stump) and spaced at 5m. Measurements of base diameter and diameter at breast height (DBH), tree height and crown diameter, all in meters (m) were taken in the managed and unmanaged plots

6.3.4. Development of allometric equation using groundtruthed data

A total of One hundred and twenty eight (128) *Prosopis* trees were randomly selected (four (4) each from the ten sample trees in the 32 plots). The measurements of basal diameter (BD), breast height diameter (DBH), tree height and crown diameter variables were taken in the managed and unmanaged plots for the development of the allometric equations.

All the 128 sampled trees were then cut down the actual weights (fresh weights) determined with a spring balance. To determine the whole tree weight, trees were cut into small sizes immediately after felling. Tree segments of weights that could be easily lifted were fastened together with a sisal twine and weighed with a spring balance until the entire tree materials were exhausted. Weights were then recorded separately for each tree.

SPSS software was used for the analysis. Exploratory analysis (variable and model evaluation) was done to find out the appropriate variables and models for estimating biomass. Stepwise regression analysis was carried out to compare diameter (DB and DBH) based biomass estimates with height and crown width based biomass estimates in Olkiramatian floodplains and Ngurumani hillslopes. Linear, Quadratic, cubic and Power regression models were applied to the one, two and three stemmed *Prosopis* basal diameter variables. Scatter plots were developed and coefficient of determination (R^2) evaluated for the relationships between the actual and estimated biomass.

Non-linear regression equations for estimating *Prosopis* biomass from previous studies (Equation 6.1, Equation 6.2 and Equation 6.3) were applied using FW and BD as the dependent and independent variables.

$Ln(FW\ (Kg)) = 0.292DB + 0.59$ (Muturi *et al.*, 2011) ……………………..Equation 6.1

$FW = \lambda * exp\ (p0 + p1 * ln(EDBH) + p2 * ln(H) + p3 * ln(SN) + p4 * ln(CW))$

(Cienciala *et al.*, 2013)…………………………………………... Equation 6.2

$FW = 0.1975\ x1.1859DBH$ (Dabasso *et al.*, 2014)……………………..… Equation 6.3

(Muturi *et al.*, 2011; Cienciala *et al.*, 2013; Chave *et al.*, 2005; Dabasso *et al*, 2014, and Henry *et al*. 2011)

Where:

> FW=Estimated biomass, BD=basal diameter, λ=correction factor, EDBH=tree equivalent diameter at breast height, H=tree height, SN=number of stems with diameter larger than 5cm, CW=crown width and p0–p4=fitted parameters, x= ratio of BD and DBH

These models (Equation6.1, Equation 6.2 and Equation 6.3) either overestimated or underestimated the predicted biomass and did not show any correlations between the actual field weights measurements and the estimated biomass. Using the same principles, other models were developed, which were found to be working for this study.

The field *Prosopis* data variables from the 128 sampled trees was also used to develop allometric equations for estimating *Prosopis* above ground biomass (AGB) collected in Olkiramatian and Ngurumani for a period of 10 months. The data was divided into one stem, two stems and three stems Prosopis trees at the base (BD). Linear, quadratic, cubic and power regression equations, using fresh weight (FW) in kgs as the dependent variable and BD (cm) as the independent variable were developed for the one, two and three stemmed *Prosopis* trees. The following models were used:-

$Y = ß_0 + (ß_1 * t)$, ……………………………….……Linear regression……..…Equation 6.4

$Y = ß_0 + (ß_1 * t) + (ß_2 * t^2)$, …………………..…Quadratic models….……Equation 6.5

$Y = ß0 + (ß1 * t) + (ß2 * t^2) + (ß3 * t^3)$ …………Cubic models…………....Equation 6.6

$Y = ß0 * (t^{ß1})$ or $\ln(Y) = \ln(ß0) + (ß1 * \ln(t)$ ……Power models…………Equation 6.7

Where:

Y = the estimated biomass (kg)

t = the basal diameter measured at a height of 30cm from the ground

$ß_{0}$, $ß_{1….}$ $ß_{n}$ are coefficients

To estimate *Prosopis* biomass and carbon stocks in Olkiramatian and Ngurumani landscapes, the above biomass estimation models were applied. The field *Prosopis* data was divided according to the sites (Olkiramatian plains and Ngurumani hillslopes). The data was further subdivided into one, two and three stemmed Prosopis biomass samples and the developed basal diameter and fresh weights relationship models applied to estimate biomass. Aggregations of biomass and carbon stocks (tons/ha) were done and averages calculated for each landscape type.

Scatter plots were developed for the single, two and three stemmed *Prosopis* trees to establish relationships between actual and estimated biomass (weights). The actual (measured weights) were plotted as the independent variables against the estimated weights as the dependent variables to determine the relationship of the measured and estimated weights. The R^2s were determined and the best models based on R^2 were selected for the single, two and three stemmed Prosopis trees based on the relationships between actual and estimated biomass (weights).

To evaluate the effect of landscape type and season on the carbon level of various carbon pools, a general linear model (GLM) and least significant difference (LSD) to separate the means were used and significant difference accepted at 5% level of probability error, (Dabasso *et al,* 2014; Steel and Torrie, 1980; Mead and Curnow, 1990; Sprugel (1983). Split-plot ANOVA were used to test for differences between the repeated measurements of biomass production in the managed and unmanaged plots.

6.4. Results and discussions

The cubic models (Equation 6.6) with R^2= 0.98 for the two stemmed trees and power models (Equation 6.7) with R^2=0.8; R^2=0.73 for the one and three stemmed trees respectively, showed significant relationships between the measured and the predicted biomass and were used in estimating *Prosopis* biomass in this study

$Y = ß0 + (ß1 * t) + (ß2 * t^2) + (ß3 * t^3)$ …………… Cubic models ………....Equation 6.6

$Y = ß0 * (t^{ß1})$ or $\ln(Y) = \ln(ß0) + (ß1 * \ln(t)$ ………Power models…………Equation 6.7

The results of the linear, quadratic, cubic and power regression models (Table 6.1 , table 6.2 and table 6.3) for the one stemmed, two stemmed and three stemmed basal diameter *Prosopis* trees showed that the power regression model was a better estimator (R^2=0.82) of the biomass in the one stemmed Prosopis trees (Table 6.1). The results also showed that the cubic regression model was a better estimator (R^2=0.98) of the biomass in the two stemmed Prosopis trees (Table 6.2). The results also showed that the power regression model was a better estimator (R^2=0.73) of the biomass in the three stemmed Prosopis trees (Table 6.3).

6.4.1. Actual and estimated biomass relationships of the *Prosopis* biomass models

Scatterplot for the single stemmed *Prosopis* trees (Fig. 6.1a) showed very strong and positive relationships between actual and estimated biomass (R^2=0.8). Scatterplot for the two stemmed

Prosopis trees (Fig. 6.1b) showed the strongest relationships between actual and estimated biomass (R^2=0.98) and the scatterplot for the three stemmed *Prosopis* trees (Fig. 6.1c) showed reasonable relationships between actual and estimated biomass (R^2=0.73).

6.4.2. Estimation of *Prosopis* biomass and carbon stocks

The *Prosopis* biomass estimates in the two landscapes of Ngurumani and Olkiramatian and in the four different density classes of dense managed, dense unmanaged, moderately dense and sparsely were compared. Ngurumani hillslopes landscape with higher rainfall amounts and lower temperatures had the highest *Prosopis* biomass (44.13 tons/ha) in the dense managed category (Table 6.4). This was followed by dense unmanaged category (43.68 tons/ha) also in Ngurumani. The lowland plains of Olkiramatian had the third and fourth highest *Prosopis* biomass estimates in the dense unmanaged (34.15tons/ha) followed by dense managed category (28.01 tons/ha) of the Olkiramatian plains. The moderately and sparsely dense categories in both landscapes recorded the lowest *Prosopis* biomass (18.75 and 3.47tons/ha in Ngurumani and 12.72 and 5.09tons/ha in Olkiramatian (Table 6.4).

Carbon is an equivalent of charcoal from a tree when all the water is evaporated and it has been estimated at 50% of plant biomass (Hoen and Solberg, 1994; Losi *et al.*, 2003; IPCC2007, 2004). Carbon stocks were estimated at 50% of the biomass (Dabasso *et al*, 2014; Henry *et al*. 2011) for the *Prosopis* plots in Ngurumani and Olkiramatian landscapes (Table 6.4). Although the biomass values for the dense managed Prosopis plots were higher than the dense unmanaged Prosopis plots, the effects of management (spacing and pruning) were not noted in the Ngurumani

Table 6.1: Regression results for one stemmed, two stemmd and multistemmed Prosopis basal diameter (cm) in Olkiramatian location of Magadi Subcounty, Kenya

a) **One stemmed *Prosopis* basal diameter**

Regression Equation	R Square	Intercept/Constant	Coefficients		
			b1	b2	b3
Linear	0.76	-43.19	7.75		
Quadratic	0.79	3.30	0.40	0.20	
Cubic	0.79	30.13	-5.92	0.60	-0.01
Power	**0.82**	**0.54**	**1.69**		

b) Two stemmed *Prosopis* basal diameter

Regression Equation	R Square	Intercept/Constant	Coefficients		
			b1	b2	b3
Linear	0.75	-103.42	20.00		
Quadratic	0.94	90.69	-25.30	2.02	
Cubic	**0.98**	**-76.66**	**35.95**	**-4.27**	**0.18**
Power	0.85	0.67	1.92		

c) Multi-stemmed *Prosopis* basal diameter

Regression Equation	R Square	Intercept/Constant	Coefficients		
			b1	b2	b3
Linear	0.67	-28.99	9.72		
Quadratic	0.70	-114.36	19.64	-0.20	
Cubic	0.70	-120.97	20.96	-0.27	0.00
Power	**0.73**	**0.94**	**1.62**		

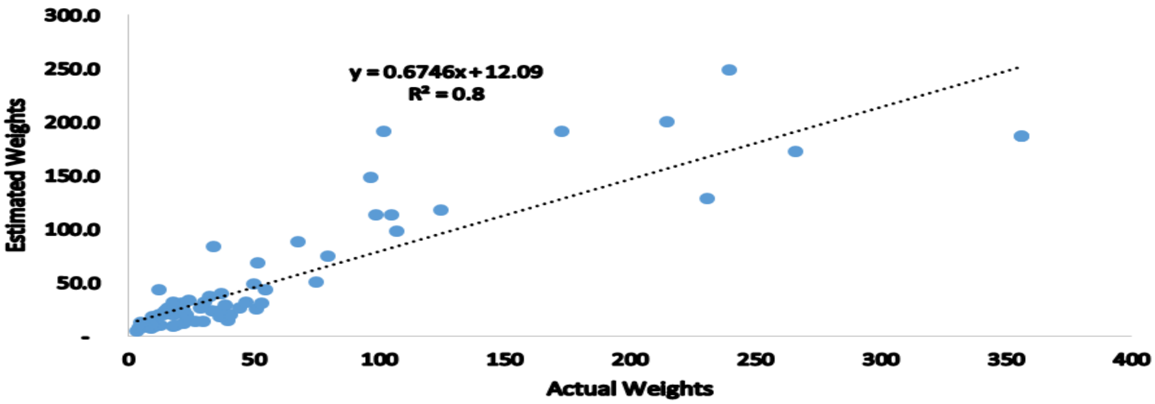


Figure 6.1a: Actual vs estimated weights of single stem *Prosopis* basal diameter in Olkiramatian location of Magadi Subcounty, Kenya

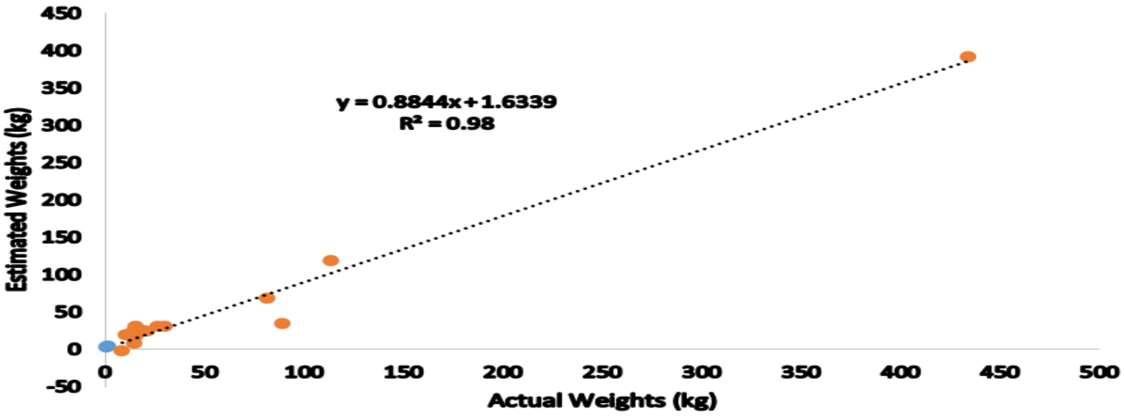


Figure 6.1b: Actual vs estimated weights of two stemmed *Prosopis* basal diameter in Olkiramatian location of Magadi Subcounty, Kenya

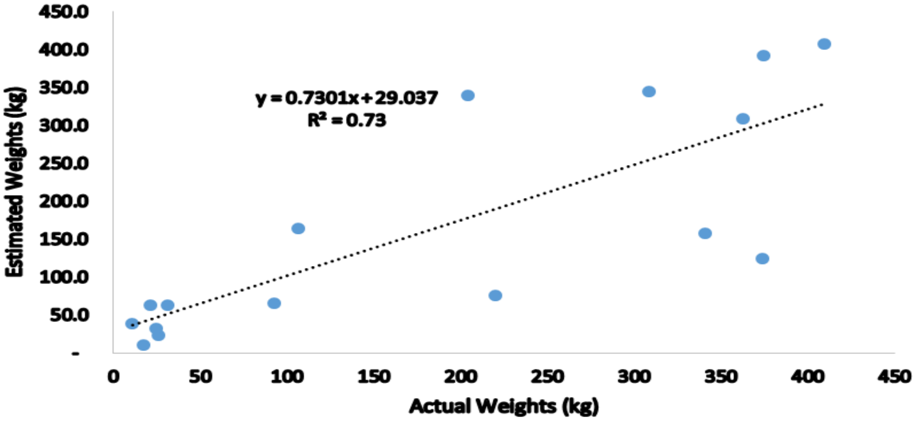


Figure 6.1c: Actual vs estimated weights of three stemmed *Prosopis* basal diameter in Olkiramatian location of Magadi Subcounty, Kenya

landscape as the differences were insignicant (Table 6.4). However, the biomass values for the dense managed *Prosopis* plots were lower than the dense unmanaged *Prosopis* plots in the Olkiramatian plots, and again there was no effect of management in Olkiramatian landscape as the differences were insignicant (Table 6.4). A longer time of obsevations might be needed for the effect of management to the realized in biomass production. Because the factor of conversion is the same, the carbon quantities echoed these of the biomass.The *Prosopis* biomass growth in the moderately and the sparsely dense clusters were significantly different in Ngurumani but not in the Olkiramatian landscape. Possible reasons included greater competitionfor the available growth resources (water and light) with other vegetation types including other *Prosopis* plants outside the sample, leading to depressed and differentiated growth.

6.4.3. *Prosopis* biomass trend over time analysis

Prosopis biomass time series trends in Olkiramatian and Ngurumani landscapes were plotted in charts with time (months) as X axis and *Prosopis* biomass as Y axis. The four lines (trends) for dense (managed and unmanaged), moderate and sparse densities were drawn and fitted with error bars (Fig. 6.2a and Fig.6.2b). The *Prosopis* biomass trends were developed for the dense and managed, dense and unmanaged, the moderately dense and the sparsely dense *Prosopis* clusters (Fig. 6.2a and Fig.6.2b). Although the biomass values for the dense managed *Prosopis* plots were consistently higher than the dense unmanaged *Prosopis* plots, the difference in the effects of thinning and pruning were not significant in the Ngurumani landscape (Fig. 6.2a). However, the biomass values for the dense managed *Prosopis* plots were consistently lower than the dense unmanaged *Prosopis* plots in the Olkiramatian plots, but again there was no effect of management in Olkiramatian landscape as the differences were insignicant (Fig.6.b). Possible reasons for the observed trends included less competition for plant growth resources (water and

Table 6.4: Biomass and carbon stocks (Tons/ha) in different *Prosopis* densities in Ngurumani and Olkairamatian landscapes of Magadi Subcounty, Kenya.

Desnity classess	**Ngurumani hillslopes**		**Olkiramatian floodplains**	
	Biomass	**Carbon**	**Biomass**	**Carbon**
Dense managed	44.13^a	22.07	28.01^a	14.0
Dense unmanaged	43.68^a	21.8	34.15^a	17.1
Moderately dense	18.75^b	9.4	12.72^b	6.4
Sparse	3.47^c	1.7	5.09^c	2.5

Means with different letter superscripts down each column are significantly different (*$P<0.05$)

light) in the Ngurumani dense clusters as compared to the Olkiramatian floodplains with higher water stress. There was little effect of management on *Prosopis* productivity in both landscapes in the dense category of plots. Nevertheless, managing Prosopis stands would benefit biomass production over time in areas where rainfall is adequate (see figure 6.2a) and a longer time frame for this type of experiment it is recommendated.

The *Prosopis* biomass growth in the moderately and the sparsely dense clusters were significantly differently in Ngurumani but not in the Olkiramatian landscape over the study period (January to October, 2014). Possible reasons included greater competition for the available growth resources (water and light) with other vegetation types including other *Prosopis* plants outside the sample.

One source of error in estimating carbon stocks in *Prosopis* forests is the lack of specific models for converting tree measurements to above-ground biomass (AGB) estimates. Log transformed (Duff *et al.,* 1994; Padron and Navarro, 2004; Alvarez *et al.,* 2011) and untransformed (Maghembe *et al.,* 1983; Padron and Navarro, 2004) basal diameters have been used for *Prosopis* biomass prediction depending on the species and nature of the stand studied. Evaluation of model development using transformed and untransformed data could not justify data transformation as reliable models were obtained with untransformed data, (Muturi *et al.,* 2011).

Chave *et al.,* (2005) estimated above ground biomass for dry forest stands using a mix of specific gravity, exponential and natural logarithm of the basal diameter in a nonlinear allometric equation. This was an attempt to improve the quality of tropical biomass estimates and bring consensus about the contribution of the tropical forest biome and tropical deforestation to the global carbon cycle.

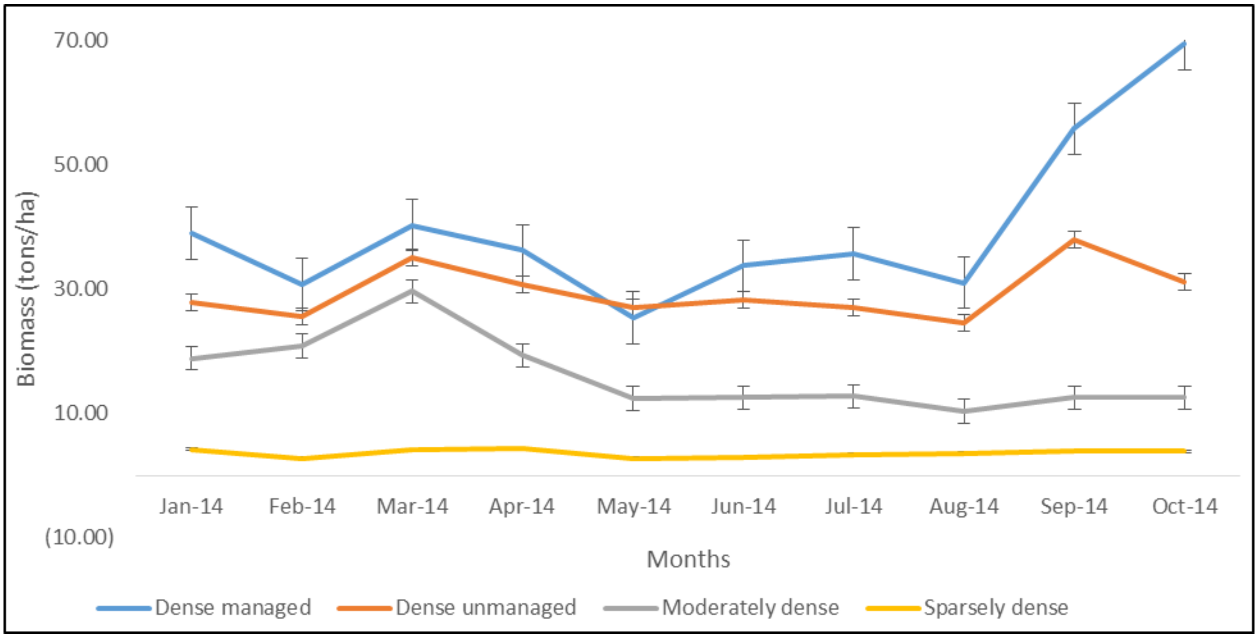


Figure 6.2a: ***Prosopis*** **biomass trends in Ngurumani landscape of Magadi Subcounty, Kenya.**

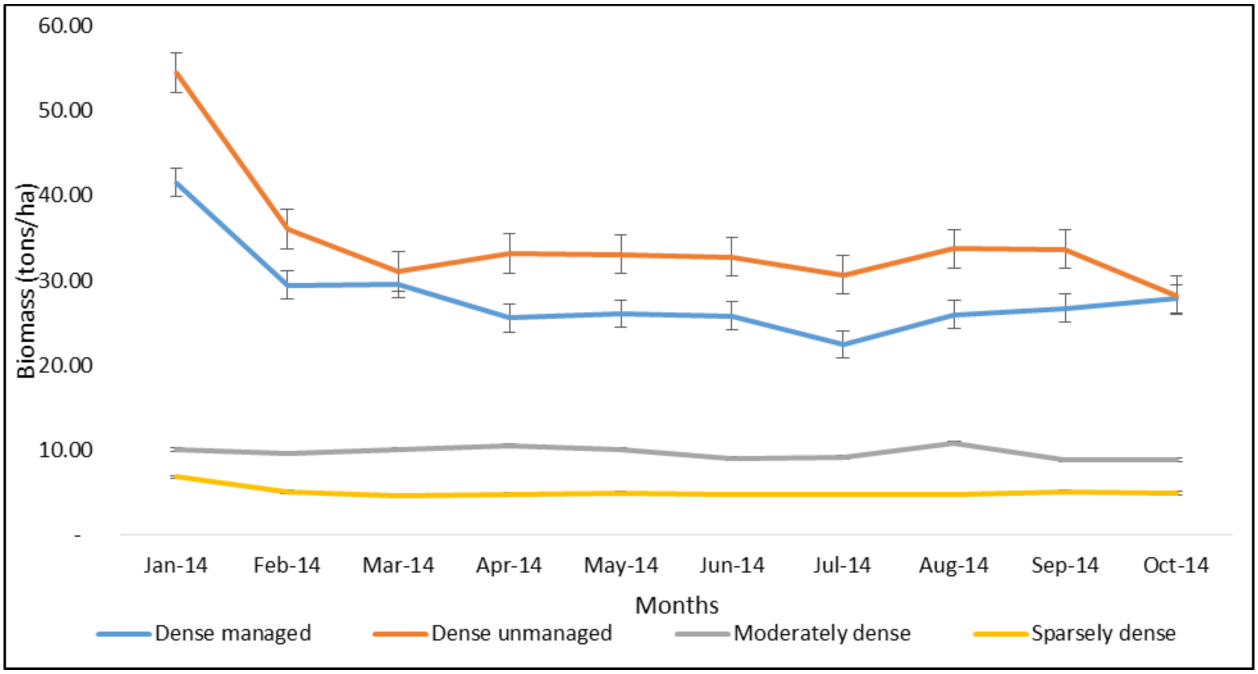


Figure 6.2b: ***Prosopis*** **biomass trends Olkiramatian landscape of Magadi Subcounty, Kenya.**

The use of allometric regression models is an important step in estimating AGB, yet it is seldom directly tested in species specific plant ecosystems. Single stem diameter biomass estimation methods (Muturi *et al.,* 2011) and (Cienciala *et al.,* 2013) have been used in estimating *Prosopis* above ground biomass in previous studies. The two estimation approaches were applied in this study and models either over estimated or under estimated the biomass compared with the fresh weights of the Prosopis biomass. The variance of the *Prosopis* fresh weight biomass and the estimated biomass was too large for application in this study. Muturi *et al.,* 2011 found that power (loglinear) models were stronger than linear models the Prosopis fresh weight biomass. However for multistemmed trees, only one stem was sampled and uniformity of tree characteristics assumed for the other stems. Cienciala *et al.,* (2013) estimated *Prosopis* biomass from multiple stems at base and at breast height using a model with a correction factor, tree equivalent diameter at breast height and fitted parameters. Power models were stronger than linear models in relating fresh weight to tree diameters.. Dabasso *et al*, (2014) and Henry *et al.,* (2011) used power allometric equation with a correction factor to estimate biomass fresh weight in Marsabit drylands of Kenya. To estimate dry biomass, the results are multiplied by 60% and the carbon content taken as 50% of the dry biomass weight.

Prosopis juliflora is usually multiple stemmed plant, which the previous models did not address significantly. Therefore models were explored for estimating multiple stemmed Prosopis using multiple diameter biomass estimation methods. Curvilinear and power models were found to be promising models for estimating P*rosopis* biomass in the drylands of Kenya. In areas with substantial water resources in the drylands, management of the *Prosopis* clusters improves the rate of growth (productivity) as opposed to the drier areas.

6.5. Conclusions and recommendations

This study found that curvilinear and power models improved the estimation of the above ground *Prosopis* biomass in the drylands. There were insignicant differences in biomass productivity between the dense managed *Prosopis* plots and the dense unmanaged *Prosopis* plots in the hillslope landscape, although the biomass in the dense managed plots were consistently higher than the unmanaged. In the floodplains landscape, however, the biomass for the dense managed *Prosopis* plots were consistently lower than the dense unmanaged *Prosopis* plots, but the differences were also insignificant. Further studies were recommended with longer time frames of obsevations to assess the effect of management on biomass production. More studies are also recommended for the development of allometric equations of estimating biomass of *Prosopis* plants whose height is less than 2 meters in height. The economics of *Prosopis* carbon stocks as *Prosopis* based carbon trade also needs further investigation.

7. CHAPTER 7: ESTIMATING *PROSOPIS* POD PRODUCTION IN THE DRYLANDS OF MAGADI IN KAJIADO, KENYA

7.1. Abstract

Prosopis juliflora pods have proven qualities for use as animal feedstuffs. This study was undertaken to establish availability of the pods in the drylands of Magadi in Kajiado County, in sufficient quantities for animal feeds production. Pods were collected and weighed once a week in randomly selected and fenced 32 plots of 900m^2 each in the Ngurumani hillslopes and the Olkiramatian floodplains. Three categories of plots based on density were marked out: dense, moderate and sparse densities. Half of the dense plots had their *Prosopis* trees pruned and thinned to allow spacing of five meters (managed dense). Weekly pods collection and weighing was done for a period of ten months including one wet season and two dry seasons. The managed dense, unmanged dense, moderate and sparse plots yielded 44 tons/ha, 25 tons/ha, 15 tons/ha and 1.3 tons/ha tones/ha in Ngurumani hillslopes and 9 tons/ha, 18 tons/ha, 1.5 tons/ha and 0.2 tones/ha in the Olkiramatian floodplains per annum, respectively. Pruning and spacing increased pod production in the well watered hillslopes landscape. Lowest and highest pod yields were recorded during the dry season and the middle of the rainy season, respectively. Thus managed *Prosopis* stands located in the hillslopes landscape could sustain commercial *Prosopis* based animal feeds production.

Keywords: *Prosopis*, pods, animal feeds, drylands

7.2. Introduction

Prosopis juliflora (Sw.) DC, (also known by many as Mathenge in Kenya, after the Government official involved in its introduction) a plant of the *Leguminoceae* family and also known as algarroba or mesquite, was introduced for land rehabilitation in Tana River County of Kenya

(Choge and Pasiecznik, 2006; Wahome *et al.*, 2008) in the 1970's and 1980's. Native to Latin Americas, the *Prosopis* genus has about 45 species (Tewari, *et al.*, 2000; Silva, 1986; Choge and Pasiecznik, 2006), is an evergreen, hardy, versatile and fast growing tree and reproduces mainly through seeds normally dispersed through dung excretions of livestock and wildlife that feed on the pods (Koech *et al.,* 2010; Mwangi and Swallow, 2005). It is difficult to eradicate and has been used successfully and profitably for timber, human food, animal feed (Choge and Pasiecznik, 2006; Wahome *et al.,* 2008).

It is estimated that one tree can produce up to 80 kg of pods in one season. In Kenya, where *Prosopis* is estimated to cover 2% of the land mass, *Prosopis* pod yields could go up to 200,000 tonnes per year (Mwangi and Swallow, 2005). The high number of viable seeds that germinate and grow very fast when in contact with moisture contributes to its adaptability to arid areas and the high densities of invasions that out-compete and suppress other plant species with relative ease. (Fagg and Stewart 1994; Pasiecznik *et al.,* 2001). Despite its invasiveness, *Prosopis juliflora* is known for its good qualities when used as animal feed.

Prosopis pods' nutrient composition is similar to that of brans and could supplement them or be an alternative to the 400,000 tons of maize and wheat bran used in the animal feed rations in Kenya (Wahome *et al.,* 2008). Its nutritive content shows a reasonable feed resource with 87% Dry matter, 10% Energy, MJ/kg, 12% Crude protein, 11% Crude fiber, 30% Nitrogen free extract, and 45% Dry matter Digestibility, (Mathur and Bohra 1993; Primo *et al.,* 1986; Wahome *et al.,* 2008; Pasiecznik *et al.,* 2001). Its utilization may provide cheap livestock feeds (Githinji *et al.,* 2009), as well help control its spread or invasion of critical resource patches. However, despite the documented properties of *Prosopis* pods as animal feed ingredients, there is little uptake by the pastoral communities and the animal feed manufactures in Kenya.

Inconsistencies in information on the productivity of the *Prosopis* and the lack of reliable supply of the *Prosopis* pods flour to the feeds factories is attributed to the low uptake. Production of *Prosopis* pods has not been well documented and the feed manufacturers and consumers lack reliable source of information to guide their decisions *(*Pasiecznik, *et al.,* 2001; Wahome *et al.*, 2008; Choge and Pasiecznik, 2006).

The demand for animal feeds produced in Kenya is highest during droughts when most of it is sourced by individuals, NGOs and the Government as part of the drought intervention to minimize livestock lossess especially in the drylands (GoK - PDNA, 2012; Nanyingi *et al.*, 2012). Coincidentally, opportunity also exists for producing livestock feeds from *Prosopis*, which is currently found in most (17 out of 22) of the Counties in the drylands of Kenya whose major economic activity, livestock production, is threatened by scarcity of forage due to recurrent droughts.

The objective of this study was therefore to estimate the seasonal pods production in the managed and unmanaged *Prosopis* natural stands in different landscapes in the drylands of Magadi of Kajiado County in Kenya. This information is expected to provide ecological and socio-economic empirical data required to inform exploitation opportunities presented by the spread of *Prosopis juliflora* in the dryalnds.

7.3. Materials and methods

7.3.1. The study Area

The study was conducted in Magadi division of Kajiado County, representing the recent *Prosopis* invasions of about 8% of the drylands of Kenya (author's estimate). The area is located in south west of Kenya (Fig. 3.1), bordering Tanzania to the south and Narok County to the west. It is situated within the following coordinates: lat/long. – 1°40'S, 36°E, 2°S, 36°15'E (Fig. 3.1): Study area in Magadi of Kajiado County)

It has a bimodal rainfall pattern with a an annual total of 460mm and a mean of 50mm, mean altitude of 600m, and mean temperatures of 32 °C . The soils are saline with soil texture ranging from very clay, clay to loam, with occasional sand. The clay types are montmorillonitic, kaolinitic and interstratified clay (Kenya soil survey 1997). The study area falls under the inner lowland and lower midland agro-ecological zones (Jatzold and Schmidt, 1983). It is sparsely populated except for the agricultural zones of Ngurumani escarpment.

The area is inhabited mainly by the Maasai communitty, who are predominantly pastoralists although a few have adapted to crop farming. The climate is hot and arid and the vegetation cover consists of Acacia, Ficus, and *Cordia sinensis* trees among other native species. The understory consists of shrubs such as Grewia spp., Boscia and Trichilia roka, and grass species that include Echinochloa haploclada (Agnew et al., 2000)

Prosopis juliflora is mainly found in Olkiramatian, Nkurumani, OlchorroOlepo and Entasopia sub-locations of Okiramatian location. These are the sites where *Prosopis* was originally introduced in Magadi Sub-county. The species is also found in other areas in Magadi, such as Musenge, Lorngosua sub-locations of Okiramatian location; Kamukuru and Kora sub-locations of Oldonyo-Nyoike location and Lenkobea sub-location of Shompole location, although the quantities are low.

The study was conducted in Olkiramatian, Ngurumani, Olchorro Olepo and Entasopia sub-locations of Okiramatian locations (Fig. 3.1), where there were well established *Prosopis* stands, with good representation of the dense, moderate and sparse density clusters, as well as the two landscapes (Floodplains and hill slopes).

7.3.2. Delineation of the landscapes and *Prosopis* density clusters

Two (2) *Prosopis* landscape strata of hillslopes and floodplains were selected purposively. Within each landscape, three (3) sites containing sparse (less than 30%) *Prosopis* density, moderate *Prosopis* density (50-70%) and high *Prosopis* density (greater than 70%) were identified purposefully. The density was validated through mapping (delineation) of areas occupied by *Prosopis* using satellite images (MODIS (250m) derived NDVI), land use & land cover and GPS data. For each site, a grid of plots (30m^2) was laid out on topo maps. Each plot in the grid was allocated a unique number to enable randomisation.

Each site had four (4) random plots of 30mx30m randomly selected and fenced off except for the high density site, where an additional four plots were selected and managed (pruning and 5m spacing between the *Prosopis* trees). The total number of plots in the whole study area of both landscapes was (2*(4+4+4+4)) = 32

Ten (10) *Prosopis* plants in each plot were randomly selected and pods measurements (weights in kg) taken in the sampled trees once every week for ten (10) months in the sparse, moderate, managed dense and unmanaged dense plots. Any vegetation undergrowth and re-growth was regularly removed in the managed plots. In the unmanaged plots observations were taken on the naturally occurring trees with no management practices applied.

7.3.3. Data collection methods and analysis

Each week, *Prosopis* pods were collected from the 32 sampling plots for 10 months covering one wet and two dry seasons for the determination of sesaonal pods production. The pods collected from each plot were weighed (in kilograms) using hand held weighing machines In addition, the trees in the sampling plots were observed to determine the start and end of their flowering, which was recorded as low, mild and heavy based on ocular judgement of the density of the flowers.

Descriptive statistics (means and standard deviations) were determined for *Prosopis* pods production using Ms excel software. Estimation of the quantities of *Prosopis* pods in the dense managed, dense unmanaged, moderate and sparse densities of the Ngurumani hillslopes and Olkiramatian floodplains landscapes were also determined and comparisons of pods production in the different densities done. Comparisons between pods production and biomass estimates were done (pods quantities under different densities, biomass and management) was also done.

Time series pods production analysis was also done using Ms excel software and comparison of the differences between pods production in the managed stands and the unmanaged stands over time in repeated measurements was also done.

The least significant difference (LSD) was used to separate the means. To evaluate the effect of landscape type and seasonal vairations on the pods production, a general linear model (GLM) was used and significant difference accepted at 5% level of probability error, (Dabasso *et al,* 2014; Steel and Torrie, 1980; Mead and Curnow, 1990). Split-plot ANOVA were used to test for differences between the repeated measurements of pods production in the managed and unmanaged plots.

7.4. Results and discussions

Descriptive statistics (means and standard deviations) of *Prosopis* pods in the dense managed, dense unmanaged, moderate and sparse densities in Ngurumani hillslopes and Olkiramatian flood plains were presented in Table 7.1

In Ngurumani hillslopes, the mean pod production was found to be highest in the dense managed plots followed by dense unmanaged plots, whereas in Olkiramatian, the mean pod production was highest in the dense unmanaged plots. This suggested that the management of the *Prosopis* trees increased pod production in the hillslopes but not in the floodplains. Reduction in competition for water and light in the dense and managed plots in the water endowed and lower temperature zone of the Ngurumani hillslopes is a possible reason for this observation (Agnew, *et al.,* 2000).The dense managed plots in Ngurumani hillslopes registered the highest total pods production (44 tons/ha) compared to the unmanaged dense plots (25 tons/ha), the moderate (15 tons/ha) and sparse plots (1.3 tons/ha). This also suggested that management improves pods production (Table 7.1) Kumar and Bhimani, (2011), in their study found out that spacing and pruning of *Prosopis* enhances pods production. However in this study it was found that in the floodplains landscape, which experiences higher aridity conditions, the managed dense plots had lower pods production compared to the unmanaged dense plots (Table 7.1).

The relationship between *Prosopis* biomass and pods production in the hillslopes and the floodplains was presented in Table 7.2. The pods production pattern was similar to the biomass production in the Ngurumani hillslopes, where there was higher biomass production and higher pods production in the managed dense plots compared to the unmanaged dense, moderate and

Table 7.1: Average annual pods production (Tons/ha) in Ngurumani and Olkiramatian landscapes of Magadi Subcounty, Kenya.

Density class	Ngurumani hillslopes		Olkiramatian floodplains	
	Mean annual production	Std. Dev	Mean annual production	Std. Dev
Dense unmanaged	24.5^{a}	1.40	17.6^{a}	2.32
Dense managed	44.3^{b}	2.21	9.3^{b}	1.21
Moderate	15.4^{c}	0.84	1.5^{c}	0.27
Sparse	1.3^{d}	0.12	0.2^{d}	0.04

Means with different letter superscripts down each column are significantly different (*P<0.05)

Table 7.2: Comparisons of annual *Prosopis* pods and biomass production in Olkiramatian and Ngurumani of Magadi Subcounty, Kenya

Location	Density	Biomass (Tonnes/ha)	Pod production (Tonnes/ha)
Ngurumani hillslopes	Dense unmanaged	52.4	24.5
	Dense managed	53.0	44.3
	Moderate	22.5	15.4
	Sparse	4.2	1.3
Olkiramatian floodplains	Dense unmanaged	41.0	17.6
	Dense managed	33.6	9.3
	Moderate	15.3	1.5
	Sparse	6.1	0.2

the sparse density plots. In Olkiramatian floodplains, however, management did not improve both the biomass but improved pods production.

7.4.1. Seasonal variation of pod yields

In the trend lines for dense (managed and unmanaged), moderate and sparse densities were fitted with error bars (Fig. 7.3a), pod production in all the *Prosopis* density classes in Ngurumani hillslopes reached its peak (dense managed - 6.0 tons/ha, dense unmanaged – 5.5 tons/ha, moderate – 2.7 tons/ha and sparse – 0.4 tons/ha) in the middle of the long rains season (May 2014), and was lowest in the dry months of February and August 2014. The dense and managed plots recorded the highest pod production quantities throughout the study period (Fig. 7.3a).

Similar trends in pod production were observed in Olkiramatian floodplains (Fig.7. 3b), reaching a lower peak (dense managed - 2.0 tons/ha, dense unmanaged – 5.2 tons/ha) in the middle of the long rains season (May) and lowest levels in the dry seasons (January-March) and (June – September). The patterns were the same in the moderate and sparse densities. The effect of management on pods production in the dense and managed plots was, however, not evident as the pods quantities in the managed plots was lower than the unmanaged plots. The possible reasons included low moisture content due to prolonged dry spells and high temperatures (Mwangi and Swallow, 2005), leading to depressed pod production in all the density classes, which was more evident in the managed plots. The observed differences in the pods production in Ngurumani hillslopes and Olkiramatian floodplains were also attributed to the lower temperatures, higher rainfall and water availability in the hillslopes than in the floodplains (Agnew, *et al.*, 2000).

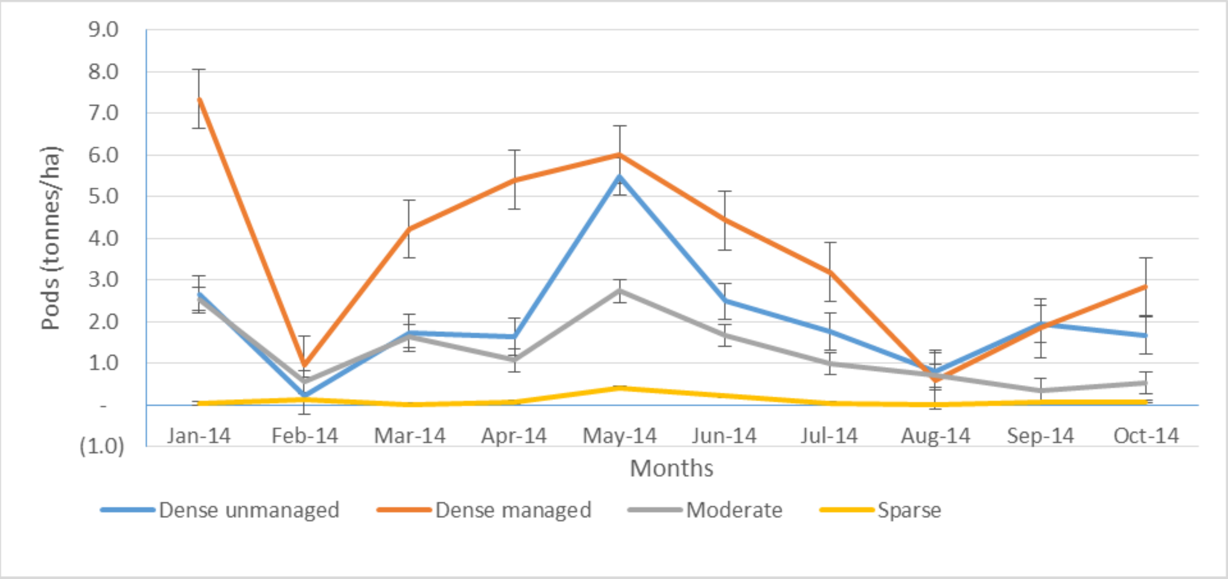


Figure 7.3a: ***Prosopis*** **pods production trends in Ngurumani of Magadi Subcounty, Kenya.**

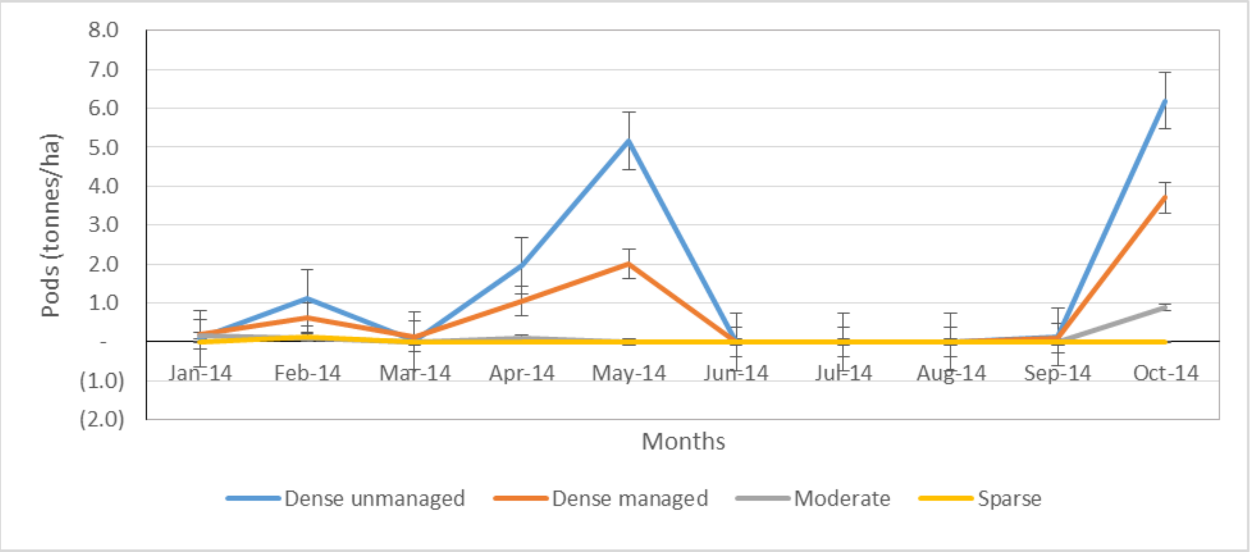


Figure 7.3b: ***Prosopis*** **pods production trends in Olkiramatian of Magadi Subcounty, Kenya.**

Prosopis pods utilization options include manufacture of livestock and poultry feeds and human food (Choge and Pasiecznik, 2006). In order to realize this potential, it is imperative that pods production dynamics are explored and the necessary information is availed to the animal feeds and human food manufacturers and the pastoralists in equal measure. The three challenges of the 21st century namely, climate change, shortage of animal feeds and impoverishment caused by lost livelihoods will be addressed, with the ultimate goal of improving livestock productivity and household incomes for enhanced pastoral resilience against climate variability (Resilience Alliance, 2010). Other challenges presented by the envisaged commercialization of *Prosopis* pods include inadequate infrastructure, the long distance to the animal feed factories and sociocultural aspects (Choge and Pasiecznik, 2006; Wahome *et al.*, 2008); the labour needs, bulkiness and processing requirements.

7.5. Conclusions and recommendations

The findings of this study suggested that management increased pod production in the hill slopes, which were found to be having better moisture regime than the floodplains. The results also showed that *Prosopis* pods production was highest at the middle of the wet season due to its early flowering (during the dry season). Pods production was evident throughout the year with low quantities during the dry seasons. There were indications of viable pods quantities in the managed *Prosopis* stands of the hillslopes landscape which could sustain animal feeds production for drought mitigation initiatives (a cow requires an equivalence of a 25kg hay bale per week for maintenance during the dry period, (Nanyingi *et al.*, 2012)) . Commercial livestock feeds venture is however a possibility that require further exploration. Therefore a study for the economics of a viable *Prosopis* pods based animal feeds ingredients, especially during the drought periods when feed ingredients are scrace, need to be undertaken.

8. CHAPTER 8: GENERAL DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

The discourse on land degradation is dominated by removal of vegetation cover and soil erosion as the main indicators thereby downplaying the role of invasive species and climate variability in the loss of land productivity (Gregorio and Latham, 2002; Agnew *et al.*, 2000). The challenges experienced as a result of *Prosopis* introduction in Kenya included loss of grazing and farm lands, loss of wetlands and also the increased predation of livestock among others (Maundu *et al.*, 2009; Choge and Pasiecznik, 2006).

Climate variability and increase in livestock population in pastoral areas have contributed to the degradation of grazing lands (WISP, 2007). This degradation has led to changes in vegetation cover and *Prosopis* is taking over the grazing lands and once introduced, *Prosopis* is hard to eradicate (Choge and Pasiecznik, 2006).

Utilization of *Prosopis juliflora* for providing high quality hard wood timber, animal feed ingredients (Mathur and Bohra, 1993), and human food (Wahome *et al*., 2008; Choge and Pasiecznik, 2006) as well as its potential to participate in the carbon credits market (Tennigkeit and Wilkes, 2008) due to its prolific growth and propagation (Pasiecznik, *et al.*, 2001) has been well documented. Despite these properties of *Prosopis,* there has been little uptake by the Kenyan pastoral communities, who are affected by the impacts climate variability (GoK - PDNA, 2012), animal feed manufacturers who might use it as a raw materials (Githinji *et al.*, 2009) or for trading in carbon credits.

The relevant information on *Prosopis* future spread patterns, potential for use in feeds and feeding enterprises and trading in carbons has been lacking (Pasiecznik *et al*., 2004; Pasiecznik *et al*., 2001). Some of this information, especially in regard to climate variability has been generated and is presented in this thesis.

Empirical ecological and socio-economic data to inform exploitation of *Prosopis* opportunities has been obtained from the study area: Climate variability, livestock populations; *Prosopis* biomass; and pods yields data is now available for Magadi, Kenya. The biomass and pod yields are affected by climate variables (rainfall and temperature), other vegetation cover, and livestock populations' dynamics. The variability of the above ground biomass production and carbon stocks have been estimated to model potential for trading in carbon credits from *P. Juliflora* and seasonal availability of pods that can be used for direct feeding of livestock or for feed manufacturing. These yields are affected by pruning, spacing, other vegetation trends, livestock population dynamics, terrain and landscape (Geesing *et al.,* 2004). Past allometric equations for estimation of the above-ground *Prosopis juliflora* biomass and carbon stocks were assessed (Cienciala *et al*., 2013; Muturi *et al.*, 2011; Felker *et al.*, 1989) and found to be inadequate for the area. However, newer, more useful ones were developed and proven sufficient to predict quantities and qualities of *Prosopis* biomass and pod yields and their seasonal variation.

Climatic data (mean monthly temperatures and mean total rainfall) were used to demonstrate climate variability over the fourteen year study period. During the same period, cattle populations decreased while sheep and goats populations remained static. Climate variability correlated positively with *P. juliflora* invasion and other vegetation cover patterns in drier parts but not in the higher altitude and wetter parts of the study area. At the same time, it correlated negatively with cattle populations. By the end of the study period, 70% of degraded bare lands had been taken over by *Prosopis.* Management of *Prosopis* was found useful only in the Ngurumani landscape where fast growth of *Prosopis* biomass was possible - the area being more humid. Management (pruning and spacing) also increased pod production in the well watered hillslopes landscape, an important point to note for when the commercialization is realized. It is also important to take note of the seasonal variation of pod yields in order to sustain *Prosopis* based animal feeds production.

The decreasing and variable rainfall amounts and patterns; and increase in mean annual temperatures in the study area with concomitant vegetation cover loss especially during the long dry seasons when livestock feed supply is limited (Ali *et al.*, 2013), make it necessary to rethink the whole livelihood issue for the area. Cattle populations may no longer be the key source of livelihoods while the sheep and goats populations have not increased sufficiently to replace the reliance on cattle. Since climatic variability is expected to continue, it is recommended that a consistent push to shift reliance for livelihoods to *Prosopis* utilization be made.

Satellite image derived NDVI and NPP can be used to point specific areas to initiate livelihood changes (Meroni *et al.*, 2014; Venus *et al.*, 2006). The economics of *Prosopis* carbon stocks for carbon trade is one such alternative livelihood source (Tennigkeit and Wilkes, 2008). Social assessments of how it can be developed is yet to be done. It may require a social and even a trading innovation (Tennigkeit and Wilkes, 2008). Consequently the affected communities can lay strategies to improve animal productivity, enhance incomes and build their resilience to climate variability.

8.1. CONCLUSIONS AND RECOMMENDATIONS

The following are the conclusions of this study:

a. In the study area, there was decreased and variable rainfall; increase in annual temperatures, increase in *Prosopis* cover, and decline in cattle populations while the sheep and goats populations remained unchanged.

b. The rate of spread of *Prosopis Juliflora* was depended on landscape and climatic conditions.

c. Cubic and power models were better predictors of the above ground *Prosopis* biomass than linear and quadratic models in the drylands. The dense managed *Prosopis* biomass was higher than the dense unmanaged *Prosopis* biomass, although differences were insignificant. In the floodplains, however, the dense managed *Prosopis* biomass was lower than the dense unmanaged *Prosopis* biomass and also the differences were insignificant.

d. Annual pod yields were 44 tons per hectare and 27 tons per hectare in dense *Prosopis* stands in Ngurumani and Olkiramatian landscapes. Pod production took place throughout the year, however, quantities were low during the dry season. Pods yields were highest at the middle (month of May) of the wet season. Silvicutural management increased pod production in the better moisture regime hillslopes.

The following are the recommendations of this study:

a. *Prosopis* utilization options present opportunities for trading in pods for feed manufacturing and biomass for carbon credits to ameliorate climate variability effects

b. During extended dry seasons or drought, animal feed shortage in Kenya could be mitigated by using *Prosopis* pods.

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10. APPENDICES

10.1. Climate date collection sheet

Year	Month	Average monthly Rainfall, mm	Average monthly Temperatures, ºC	Average monthly *Relative humidity*	Average monthly Wind speed, m/sec	Average monthly Wind direction	Atmospheric pressure	Dew point	Radiation	Soil moisture
2000	1									
2000	2									
2000	3									
2000	4									
2013	1									
2013	2									
2013	3									
2013	4									
2013	5									
2013	6									

10.2. Livestock Population data collection sheet

Year	Magadi Locations	Cattle	Sheep	Goats	Camels	Donkeys	Pigs	Chicken	Bee Hives
2000	Magadi								
2000	Shompole								
2000	Oldonyo-nyoike								
2000	Olkiramatian								
2001	Magadi								
2001	Shompole								
2001	Oldonyo-nyoike								
2001	Olkiramatian								
2013	Magadi								
2013	Shompole								
2013	Oldonyo-nyoike								
2013	Olkiramatian								

10.3. *Prosopis* biomass data collection sheet for allometric equations

Data recording – once a month; Name of data recorder________________________

Plot no._______, Site no._______, Density ___________, Date of recording__________

Plot Name	Plot No.	Management (yes/no)	Tree No.	BD (base-m)	DBH (middle-m)	Crown width-m	Tree Height-m	No. Of Branches @1m	Greenness	Observations
	1	0	1							
	1	0	2							
	1	0	3							
	1	0	4							
	1	0	5							
	1	1	6							
	1	1	7							
	1	1	8							
	1	1	9							
	1	1	10							
	2	0	1							
	2	0	2							
	2	0	3							
	2	0	4							

	2	0	5							
	2	1	6							
	2	1	7							
	2	1	8							
	2	1	9							
	2	1	10							
	3	0	1							
	3	0	2							
	3	0	3							
	3	0	4							
	3	0	5							
	3	1	6							
	3	1	7							
	3	1	8							
	3	1	9							
	3	1	10							
	4	0	1							
	4	0	2							
	4	0	3							
	4	0	4							
	4	0	5							
	4	1	6							
	4	1	7							

	4	1	8							
	4	1	9							
	4	1	10							

10.4. Pod production data collection sheet

Density___________________Name of data recorder______________________

Plot no._______, Site name_______, Date of recording__________

Plot Name	Plot No.	Management (yes/no)	Tree No.	Quantity of pods collected (kg)	Start of flowering (date)	End of flowering (date)	Start of mature pod production (date)	End of pod production (date)	Observations
	1	0	1						
	1	0	2						
	1	0	3						
	1	0	4						
	1	0	5						
	1	1	6						
	1	1	7						
	1	1	8						
	1	1	9						
	1	1	10						
	2	0	1						
	2	0	2						
	2	0	3						

	2	0	4						
	2	0	5						
	3	1	7						
	3	1	8						
	3	1	9						
	3	1	10						
	4	0	1						
	4	0	2						
	4	0	3						
	4	0	4						
	4	0	5						
	4	1	6						
	4	1	7						
	4	1	8						
	4	1	9						
	4	1	10						

10.5. Vegetation and *Prosopis* productivity data collection sheet

Plot no._______, Site no._______, Partition No.________Date of recording__________

Year	Month	NDVI	NPP	Land cover (Vegetation type)	Land use (Human activity)	Soil Type	Observations
2000	1						
2000	2						
2000	3						
2000	4						
2000	5						
2000	6						
2013	1						
2013	2						
2013	3						
2013	4						
2013	5						
2013	6						