A pathway for sustainable development of mixed crop-livestock systems in semi-arid Kenya: an integrated approach to soil nutrient management

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By

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Abstract

Rainfall variability and declining soil fertility are predicaments to sustainable food production. The vagaries of rainfall and the limitations of soil nutrient are mostly felt among the small-holder farmers within arid and semi-arid areas (ASAL) of Sub-Saharan Africa. Over 70% of Kenya's landmass is either arid or semi-arid. Marsabit-central Sub-County is located within ASAL areas of Kenya and rain-fed production systems provide the primary source of livelihoods. However, the pattern of land use, and the changeability of forage biomass with the rainfall variability has received little attention. Furthermore, the crop production practices, characteristics of soils, and particularly the nutrient balance, has lacked conclusive study.

This study employed remotely sensed data to reveal the land use classes. Additionally, rain gauges and spatial modelling were used to unveil the variability of rainfall and forage biomass. Using field measurements, the characteristics of soils and farmer's crop yields were investigated. Field assessments also included quantification of nutrient flows, and thereby nutrient balance in the crop fields. Finally, by scenario analysis, this work explored alternatives for sustainable food production based on integrated crop and livestock systems.

This study showed that crop fields and grazing lands are important land use classes in Marsabit-central. The spatio-temporal variability of rainfall influenced production of forages, the number of livestock fed and availability of manure. Nitrogen is the deficient soil nutrient and the measured nitrogen balance ranged from -41.7 to -66.3 kg/ha/season in maize fields and -28.8 to -30.2 kg/ha/season in bean fields. Nevertheless, the collectable livestock-mediated manure is 5.0-12.0 x 10^6 kg and 1.5 x 10^6 kg in long and short median rain seasons, respectively.

Better use of livestock manure can sustain the nitrogen balance and also improve maize grain yields from current 1.1 t/ha to 2.0-4.0 t/ha and bean grain yields from current 0.7 t/ha to 0.8-1.5 t/ha. Sustainable food production in Marsabit-central farms lie in integrated crop-livestock systems, and manure plays a central role in reclaiming the declining soil fertility.

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Acronyms and Abbreviations

ANOVA	Analysis Of Variance
asl	Above Sea level
ASAL	Arid and Semiarid Lands
C	Carbon
^{o}C	Degree Celsius
cm	Centimetre
CN	Carbon Nitrogen
DEM	Digital Elevation Model
dd	Decimal Degree
Df	Degree of Freedom
DM	Dry Matter
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agricultural Organization of United Nations
g	Gram
GBP	Great British Pounds
GIS	Global Information System
GL	Grazing Lands
Gov’t Met	Government Meteorological service
GoK	Government of Kenya
GPS	Global Positioning System
Ha	Hectare
HH	Household
HSD	Tukey’s Honestly Significant Difference
ILRI	International Livestock Research Institute
IN	Nutrient Inputs
KALRO	Kenya Agricultural and Livestock Research Organization
K	Potassium
KES	Kenya Shillings
kg	Kilogram

km	Kilometre
l	Litre
m	Metre
ml	Millilitre
mm	Millimetre
n	Sample Size
nm	Nanometre
N	Nitrogen
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra-Red
OUT	Nutrient outputs
pH	Potential of Hydrogen
P	Phosphorous
ppm	Part (s) per million
PoE	Probability of Exceedance
Q1	First Quartile
Q3	Third Quartile
RUE	Rain Use Efficiency
SD	Standard Deviation
Se	Selenium
SE	Standard Error
SLC	Scan Line Corrector
sp	Species
SSA	Sub Saharan Africa
t	Tons
TLU	Tropical Livestock Unit
UK	United Kingdom
USGS	United States Geological Survey
v	Version
yr	Year

Chapter 1 : Introduction

1.1 Context

Globally, crop and livestock agriculture provides livelihood to millions of people. The need to continue feeding growing human population exerts pressure on crops and livestock production. The necessity to increase food production while maintaining the integrity of the environment is currently the focus of policy makers, farmers and agricultural scientists (Eickhout, Bouwman et al. 2006, Vávra, Daněk et al. 2018). However, the agricultural inputs are not increasing with same pace at which demand for food products are increasing. Instead, the climate variability and environmental degradation are undermining food production. Variable rainfall and declining soil nutrients are the major predicaments to food production. These predicaments are more intense in Sub-Saharan Africa (SSA) more than other parts of the world.

Irrigated agriculture is believed to be a remedy against variable rainfall and also mineral fertilizer seen as a quick solution to declining soil fertility. The infrastructure for irrigated agriculture and the cost of mineral fertilizer are beyond the means of small-holder farmers in SSA. Yet, about 80% of farmers in SSA are small-holder farmers (Clover 2003) (Senbet and Simbanegavi 2017).

Alternative production options are necessary to sustain small-holder farming system in SSA. A production system that is affordable to farmers, environmentally sound while improving crop yields is desirable. In SSA, mixed small-holder farming systems, mainly involve crop and livestock sub-systems. Crop-livestock systems offer opportunity for sustainable intensification.

There are potential intensification pathways within the crop-livestock integration, and therein lies alternatives for improving food production in SSA. Crop-livestock production in SSA involve crop fields and livestock subsystems. In these systems, livestock moves and graze where there is a better pasture, utilizing the variable environment. The same livestock moves back to graze on non-food crop biomass, thus bringing manure for crop fields. Therefore, livestock plays critical role in transferring manure for soil fertilization.

Manure is the affordable source of input for small-holder farmers in SSA. The importance of manure for maintaining soil fertility has been widely recognized (Murwira, Swift et al. 1995, Materechera 2010). Livestock-mediated manure provides opportunity for sustainable intensification of SSA agriculture. Therefore, sustainable use of livestock manure is the potential remedy against low crop yields and deteriorating soil fertility in SSA.

1.2 Research aim and objectives

The aim of this research work is to explore sustainable approach to soil nutrient management based on integrated crop-livestock systems in semi-arid environment. The study investigates spatial and temporal variability of rainfall. In addition, soil nutrients is important for production of food and livestock feed. Soil nutrients and rainfall pattern in the realm of crop-livestock integration is central to this study.

The following are the objectives of this study:

1. To reveal the main land use classes in Marsabit-central sub-county. The main land use classes are identified and mapped. In addition, Normalized Difference Vegetation Index (NDVI) values are calculated as a measure of land productivity.
2. To understand the spatial and temporal variability of rainfall and its influence on production of forage biomass.
3. To identify the soil characteristics and crop production practices in Marsabit-central farms. The dominant food crops and nutrient flows within the farmer's crop fields are studied. Additionally, nutrient balance is calculated.
4. To explore various options and recommend sustainable food production alternatives. Different scenarios of food production are explored and alternatives for sustainable food production system are suggested.

1.3 Study area

1.3.1 Location of the study area

The study area is located in northern Kenya, Marsabit County. Marsabit County borders Southern Ethiopia to the North. It also borders Lake Turkana to the West. The area of study is in Marsabit-central sub-County, and is located within 37 degree 57 minutes to 38 degree 12 minutes Eastings, and 2 degree 12 minutes to 2 degree 24 minutes Northings (Figure 1-1 and Figure 1-2).

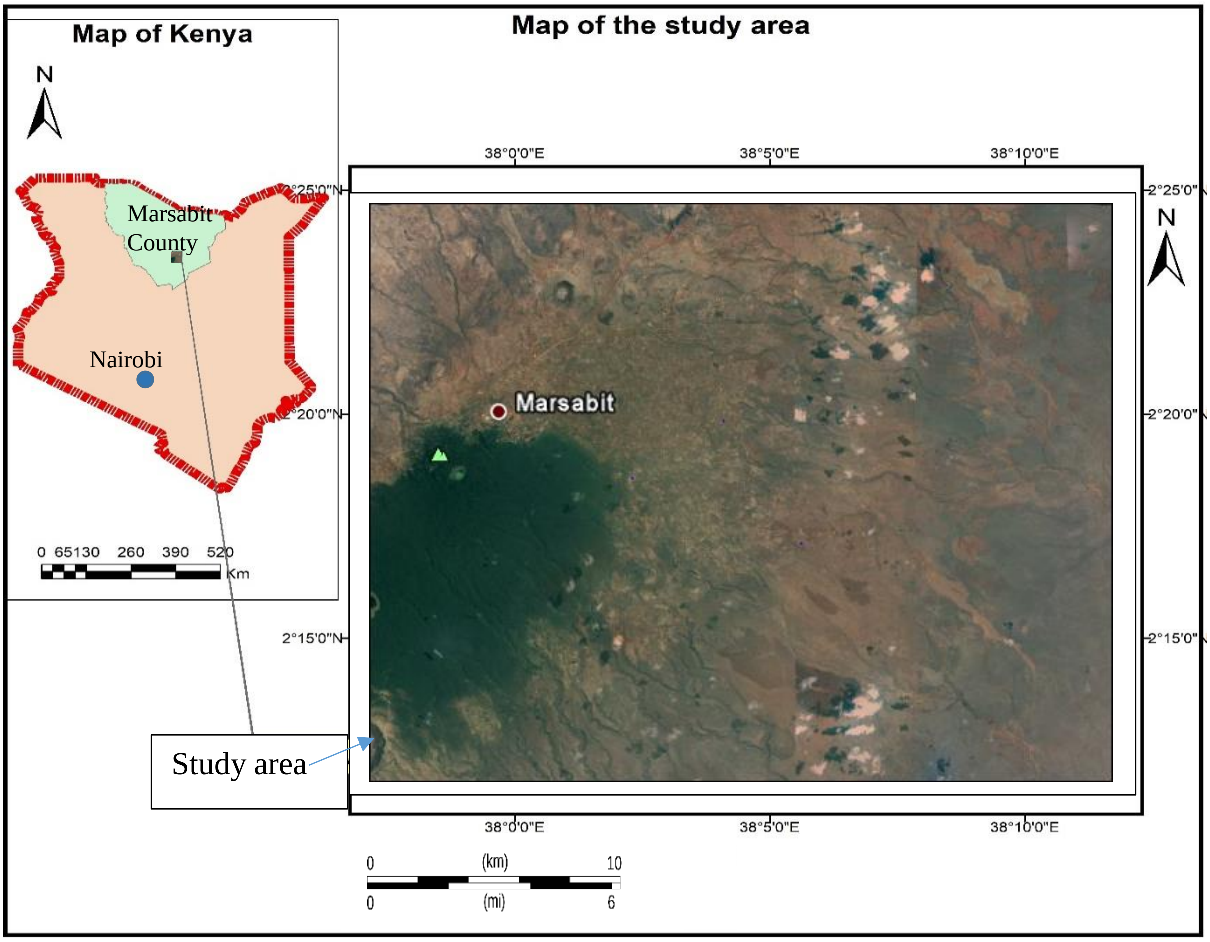
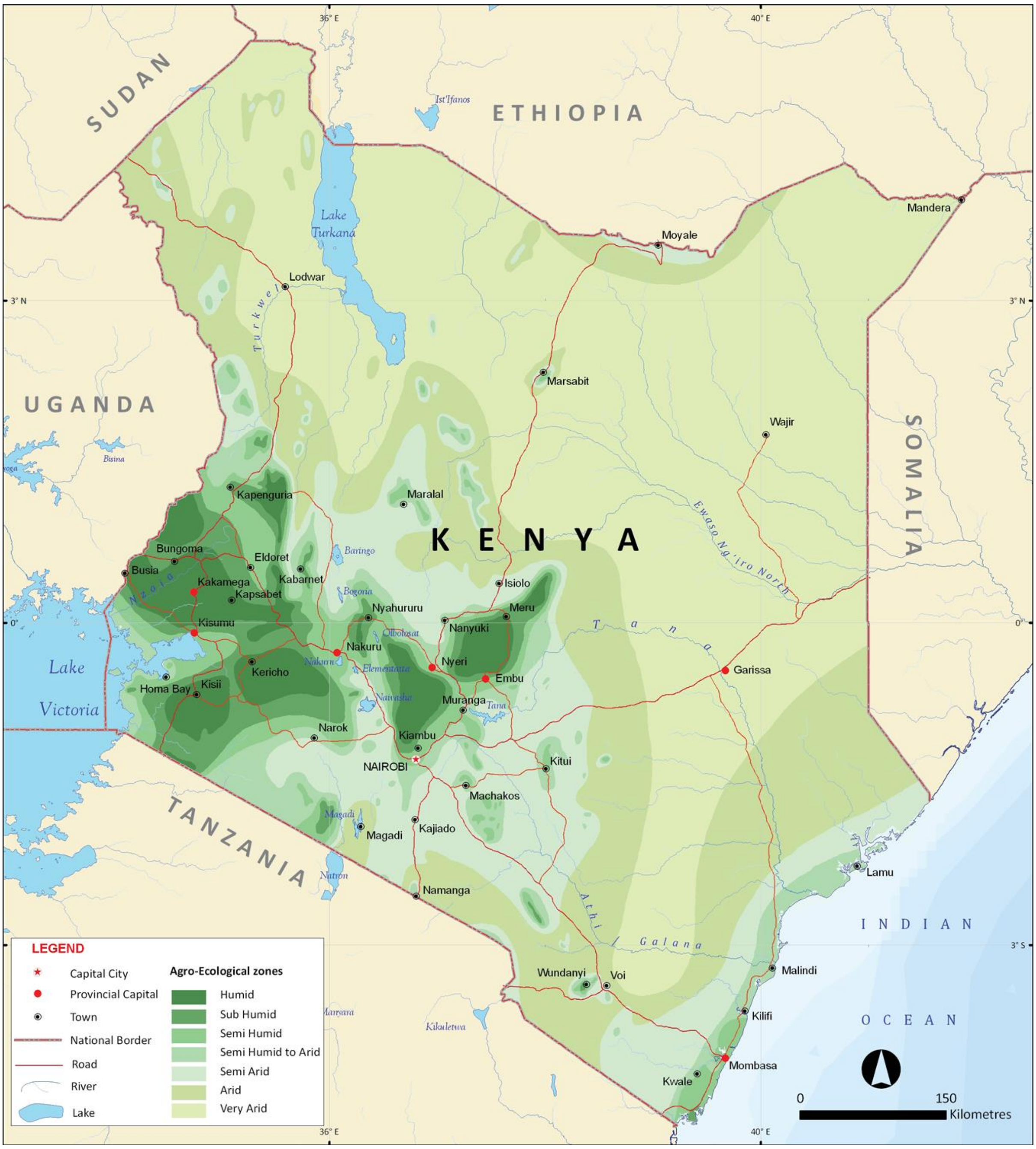


Figure 1-1: Location of the study area

1.3.2 Agro-ecological zones of Kenya

Kenya has diverse agro-ecological zones ranging from I-VII. Agro-ecological zone I is humid while zone VII is very-arid. The study area, Marsabit-central, falls in zone IV and zone V. The high altitude crop fields and grazing areas of study fall within semi-humid to semi-arid agro-ecological zone. Moving further into the grazing lands, the agro-ecological zone changes to semi-arid and then further beyond the area of study it changes to arid agro-ecological zone (Figure 1-2) (Table 1-1) (Sombroek, Braun et al. 1982).



(Jaetzold, Schmidt et al. 2009)

Figure 1-2: Agro-ecological zones of Kenya

Table 1-1: Characteristics of agro-ecological zones and farming systems in Kenya

Zone	Moisture Index (%)	Climate classification	Average annual rainfall (mm)	Average annual potential evaporation (mm)	Vegetation	Farming systems
I	>80	Humid	1100-2700	1200-2000	Moist forest	Dairy, sheep, coffee, tea
II	65-80	Sub humid	1000-1600	1300-2100	Moist and dry forest	Maize, pyrethrum, wheat, coffee
III	50-65	Semi humid	800-1400	1450-2200	Dry forest and moist woodland	Wheat, maize, barley, beans, cotton
IV	40-50	Semi-humid to semi-arid	600-1100	1550-2200	Dry woodland and bush land	Cattle, sheep, barley, sunflower, maize, cotton, cashew nuts
V	25-40	Semi-arid	450-900	1650-2300	Bush land	Beans, sorghum, livestock
VI	15-25	Arid	300-550	1900-2400	Bush land and scrub land	Ranching and irrigated agriculture
VII	<15	Very arid	150-350	2100-2500	Desert scrub	Nomadism

(Sombroek, Braun et al. 1982, Kabubo-Mariara and Karanja 2007, Jaetzold, Schmidt et al. 2009)

Furthermore, Kenya has 24 different classes of soils (Figure 1-3). The study area, Marsabit-central, is mountainous and has deep and well drained volcanic soils. There is no salinity and sodicity problems in Marsabit-central, and the soil texture is clay. In the appendices, the map unit symbols MV1 and MV2 represents the study area (Appendix 10 and Appendix 11).

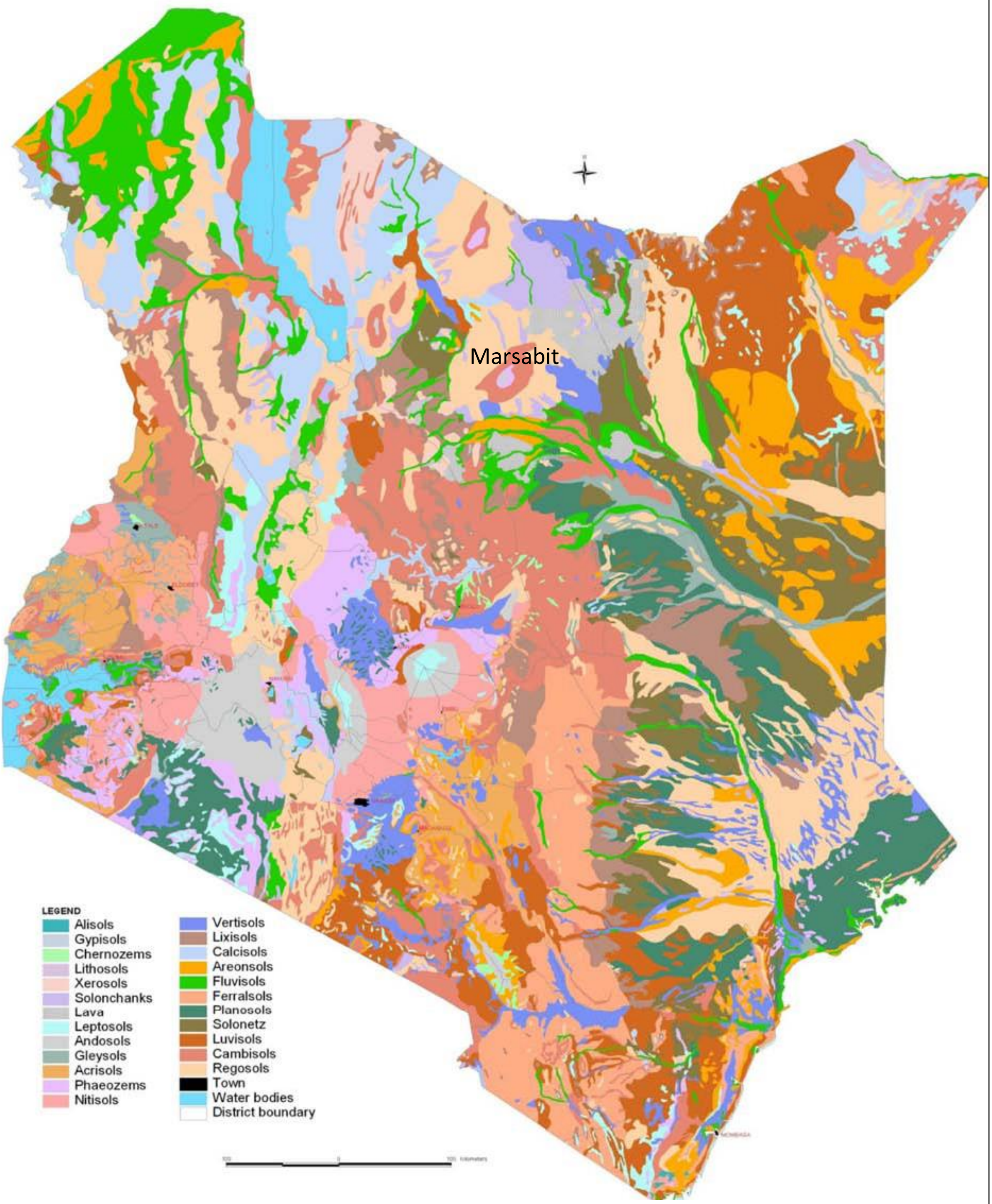


Figure 1-3: Soil map of Kenya Source: Gok, 2014

Production systems in the area of study

Crops and livestock production are the main economic activities in Marsabit-central Sub-County. Crop fields and local grazing lands are owned by individual farmers, and are found in upper 900-1300 m asl, while the low-lying area of about 500-900 m asl are used for livestock grazing and is commonly owned (Figures 1-4, 1-5, 1-6, 1-7).

Figure 1-4: Image showing good grazing land

Figure 1-5: Image showing part of poor grazing land

Figure 1-6: Aerial view of crop fields and settlements

Figure 1-7: Image showing crop fields and grazing lands

Livestock are mainly grazed in upper home fields during dry season, but during wet season, livestock are moved to lower common grazing lands. Livestock stays and grazes in the lower common grazing lands until crops are harvested, and moves back after harvesting of crops to feed on the individual upper grazing lands and on non-food crop biomass (Table 1-2).

Table 1-2: Gantt chart showing the agricultural activities in Marsabit-central sub-county

Activities	Main activities in the months of the year											
	January	February	March	April	May	June	July	August	September	October	November	December
Long rain period				■	■	■	■					
Short rain period										■	■	■
Planting of crops			■	■						■		
Weeding of crop fields					■	■						■
Harvesting of beans	■					■	■					
Harvesting of maize		■					■	■				
Livestock grazing in lower common grazing lands			■	■	■	■				■	■	■
Livestock grazing in upper home fields	■	■					■	■	■			

1.4 Thesis structure

This thesis comprises of the following seven chapters:

Chapter 1 contains the introduction. It involves setting the work in the context of relevant scientific arena. In addition, the aim and objectives of the thesis are detailed in this chapter. The geographical location and description of the study area are made. Finally, the structure of the thesis is elaborated.

Chapter 2 involves the review of the literature. These involve reviewing the existing knowledge on the area of land use classes, rain and nutrient utilization for production of food. Additionally, the existing gaps in the area of study are identified.

Chapter 3 reports on the main land use classes in the area of study. The map showing different land use types is presented. Also, the Normalized Difference Vegetation Index (NDVI) of the area is shown.

Chapter 4 presents the trend of historical rainfall and the exceedance probabilities for annual and seasonal rainfall at Marsabit town. Additionally, the spatial and temporal heterogeneity of rainfall, and its influence on production of forage biomass is shown. The variability of forage biomass from upper home fields to lower grazing lands is revealed.

Chapter 5 describes the socio-economic characteristics of farming communities in Marsabit-central. The chemical and physical properties of soils are presented and the most limiting soil nutrient is specified. The potential nutrient inflows and outflows are reported. The soil moisture in various crop fields and in different soil depths is shown. Also, maize and bean yields under farmer's practices are described. The field-level nutrient balance is reported. In addition, the manure production and its characteristics are shown. Finally, the rain use efficiencies of crop grains and total aboveground crop biomass are detailed. Quantifiable sustainability indicator for Marsabit-central food production systems is recommended.

Chapter 6 reports on the scenario analysis. The key assumptions behind the scenario analysis and the measurements used for running the scenarios are shown. Collectable manure, based on the seasonality of rainfall and livestock grazing distance is presented. Different scenarios of crop production including sole maize production, sole bean and maize-bean rotation systems, under manure fertilization are detailed. The NPK balance under manure fertilization is shown. Finally, the hectares of grazing lands required to fertilize crop fields is revealed.

Chapter 7 restates the objectives and the key results. The contribution of the thesis to theory, policy and food production practices are also presented. The potential research areas for future work are suggested.

Chapter 2 : Review of the Literature

2.1 Introduction

The determinants of agricultural productivity are resources such as rain and soil nutrients. In most parts of the world, these resources are limiting and hamper full potential of food production. Demand for food products is increasing owing to heightening world human population. Human population is estimated to reach 1650 million in Sub-Saharan Africa, and 9 billion in the world, by 2050 (Laurance 2001, Ararso, Schultz et al. 2009). This can lead to high demand for more food which requires increase in agricultural resources to boost food production. However, it has not been possible to meet the demand of agricultural resources at the pace at which human population and need for food products are increasing. The most challenging problem during our lifetime remains meeting demand of food production with variable rain and soil nutrient resources. The challenges of variable rain and limiting soil nutrients are likely to continue in the foreseeable future.

In Africa, media has been blaming variable rain for reducing food production. However, even in the cropping seasons perceived by farmers and government agencies as "best" rain seasons, food production has been low. This is attributable in part to nutrient mining (Drechsel, Gyiele et al. 2001, Descheemaeker, Amede et al. 2010). The continuous mining of nutrients with little nutrient input has characterized the production systems in African Agriculture. Continuous utilization of nutrient stock without replenishing can have a negative effects on the food sustainability and ecosystem health.

The unevenness of rain coupled with scarce soil nutrients are likely to be more heavily felt in Africa than anywhere else, where agriculture and livestock production provides over 80% of sources of livelihood (Gladwin, Thomson et al. 2001). The variable rain and limited nutrients are already reducing potential yield of crop grains and biomass production, and further negatively impacting on the human wellbeing (Tittonell and Giller 2013). This is more pronounced in arid and semi-arid areas of SSA.

Over 70% of landmass in Kenya is either arid or semi-arid (ASAL) (GoK 2011b)(Jaetzold, Schmidt et al. 2009). Marsabit, northern Kenya is located within ASAL areas of Kenya. In Marsabit-central, the status of rainfall variability and soil nutrients is unclear. Providing sustainable solutions to limiting agricultural resources start with research efforts. So far research efforts in understanding the food production systems in Marsabit-central Sub-County is minimal. Scarcity of previous research work in rain and soil nutrients require initial understanding of the existing land-based activities. Therefore, land use classification is the pre-requisite effort for understanding the food production pattern in Marsabit-central Sub-County.

2.2 Land use classification

Land is the key natural resource for the survival of humans, livestock and plant life. Land use classification involves categorizing of different land use types. Globally, land use is changing from one land use class to another. This is caused by climate variability and also by changing need of human population. Understanding land use classes is necessary for sustainable use of the land resources (Rahman, Kumar et al. 2012).

Land use classification plays a vital role in generating land use map. Land use map displays various land use classes within a specified geographical area. It aids in monitoring, planning and sustainably managing land resources. Land use map is an important decision making tool.

In Kenya, the existing major land use classes include: crop lands, grazing lands, water bodies, forests and built-up urban and rural environment (Marshall, Norton-Griffiths et al. 2017) (Jansen and Di Gregorio 2003). The land use classes in Kenya differs spatially with the Counties. In Marsabit County, northern Kenya, there is no functional land-use class map. However, the area has extensive grazing lands and areas of arable agriculture on mountains and within oasis parts of the county. Marsabit-central sub-county is occupied by crop-livestock farmers using both mountain areas for crop agriculture and the grazing lands for livestock production. Land use map can guide the county government of Marsabit and other development partners in sustainable use of land resources.

Remote sensing and GIS-based tools are important applications for generating usable land use maps. The efficacy of remotely sensed data and GIS tools in producing land use classes has been widely accepted (Rajan, Shukla et al. 2015) (Wondrade, Dick et al. 2014). This is more important in remote areas where first-hand studies are scarce. Erdas Imagine is one GIS tool that can perform land use classification. Additionally, this tool can perform both supervised and unsupervised land use classification. Supervised classification is user-guided, while unsupervised classification is conducted by the software without the input from the user (Bahadur 2009).

Numerous studies have used supervised classification method to perform land use classification (Islam, Jashimuddin et al. 2017) (Nurwanda, Zain et al. 2016, Kangabam, Selvaraj et al. 2018). This classification method involves use of training areas, of known land classes, to record the 'spectral signature' of colours that represent certain land use classes. Supervised classification method requires user to have done ground-truthing or having previous knowledge of the study area (Wondrade, Dick et al. 2014, Zhang, Tiyip et al. 2015). Maximum likelihood classifier is a common method of supervised classification (Zhang, Tiyip et al. 2015). To ascertain the quality of the resultant land use classes, accuracy assessment is necessary.

2.2.1 Accuracy assessment

In remote sensing and GIS, accuracy assessment give insights about the quality of the produced land use classes. This assessment illustrates the percentage of pixels correctly classified. Accuracy assessment tool is in-built within the signature editor of Erdas Imagine. Error matrix is the common way of presenting accuracy levels of the land use classification (Ikiel, Ustaoglu et al. 2013).

2.2.2 Normalized Difference Vegetation Index

Normalized Difference Vegetation Index (NDVI) measures difference between near-infrared and red light. The vegetation absorbs red light and reflects near-infrared. Healthy vegetation reflects more near infra-red and green light, but absorbs more red and blue light. The degree of greenness reflects level of chlorophyll concentrations. Satellite sensors, for example, Landsat, has necessary bands with near-infrared (NIR) and RED. In the case of low reflectance in the RED channel, and high reflectance in the NIR channel, this results in high value of NDVI, indicating, high vegetation productivity (Meera Gandhi et al 2015, Rouse et al 1974).

The aboveground vegetation productivity of different land use classes can be understood from the values of Normalized Difference Vegetation Index (NDVI).

Normalized Difference Vegetation Index (NDVI) is the measure of vegetation condition. It involves measure of greenness. NDVI uses the near infra-red (NIR) and the visible red (RED) (Elmore, Mustard et al. 2000). It is calculated as follows:

$$NDVI = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

NDVI ranges from +1 to -1. The positive numbers represent healthy vegetation while the negative numbers represent unhealthy vegetation, bare land, stones or water bodies (Basommi, Guan et al. 2015). NDVI can be used for measuring the status of land degradation and also to measure the productivity of the land.

The values of NDVI and the general productivity of land use classes is in part determined by rain and soil nutrients. NDVI is high in areas with better rain and low in dry areas. Rain is an important resource in arid and semi-arid areas of Kenya, and determines the sustainability of crop-livestock systems.

2.3 Rain use for agricultural production

Agricultural sector uses the largest percentage of water, utilizing about 80-90% of physical water resources in the world (Hamdy, Ragab et al. 2003). This is mainly through irrigated systems. However, rain-fed agriculture is still today the most common food production system. About 95% of agricultural land in Sub Saharan Africa is under rain-fed systems (Parr, Stewart et al. 1990). Irrigated food production system covers only a small portion. Further, rain-fed agriculture feeds over 60% of population in SSA. The major bottleneck in SSA is low agricultural productivity, which is 0.5 to 1.5 tonnes per hectare in a rain-fed agriculture (Mucheru-Muna, Pypers et al. 2010). However, the potential yield in SSA is 4 - 6 t/ha and 2 - 3 t/ha for maize and bean grain yields, respectively (Rockström and Falkenmark 2000).

The rain-fed system in Sub-Saharan Africa will remain important source of food now and beyond, despite operating under continuously variable rainfall pattern.

In Kenya, there is a bimodal rainfall pattern. The long rain starts from March/April and ends July/August, while the short rain starts around October/November and ends December. The start, duration and end of the rain season cannot be precisely predicted due to high climate variability. This variability is more pronounced within the arid and semi-arid areas of northern Kenya.

Despite the importance of rainfall in rural agricultural areas of Kenya, the data on rainfall has been vague at its best and non-existent in remotely-located ASAL areas of Kenya. This is occasioned by limited gauged station. Consequently, variability of rainfall, especially with space, has been blurry in ASAL areas of Kenya and other similar regions of SSA countries.

Rain Use Efficiency (RUE)

RUE entails portion of rain put into productive use. It is the ratio of aboveground net primary productivity to seasonal or annual rainfall. The necessity to know whether each drop of rain has been put to productive transpiration is gaining importance, especially in SSA where rainfall is limited and variable. Previous work used the ratio of grain yields to the total precipitation to determine RUE. Other studies used the ratio of total aboveground biomass to the total precipitation to determine RUE (Thierfelder and Wall 2009, Droppelmann, Snapp et al. 2017). However, the latter gives indication of total rainfall used for beneficial transpiration, and therefore better explains the productivity of the rainfall.

The difference between RUE and Water Use Efficiency (WUE) has not been explicit. WUE has been defined as the ratio of carbon dioxide assimilation to transpiration (Tang J et. al. 2006). WUE is also defined as amount of biomass or grain yields produced per unit of water resource. Water resource includes rain, surface or ground water (Wallace JS 2000, Kang S et al.1998). The latter definition of WUE is similar to definition of RUE. This work concerns RUE and for the purpose of this study WUE and RUE are the same.

Although drought may lead to low yields in SSA, the minimal portion of rain put into beneficial use is also a predicament. It is reported that only about 10% of rain that falls to the ground are made into beneficial use of food production. About 70-80% of rain that falls in arid and semi-arid areas of SSA is lost. 30-50% of this rain evaporates, 10-25% is lost through surface run-off and 10-30% goes down through deep percolation (Rockström, Barron et al. 2002). There is low RUE across small-holder farmers within SSA.

In SSA, putting each drop of rain into productive use is commendable strategy against vagaries of climate. There are various technologies suggested for improving RUE in SSA. These include: rainwater harvesting for supplemental irrigation, mulching, use of green and organic manure, and also breeding of water-efficient crops. In rain-fed crop production system, surface soil management and nutrient management practices have improved RUE by 15-40% (Hatfield, Sauer et al. 2001).

Additionally, some studies have asserted importance of rainfall management in food production systems of SSA (Haile 2005, Kurukulasuriya, Mendelsohn et al. 2006, Barrios, Ouattara et al. 2008). For example, Rockström and Falkenmark (2000), showed that rainwater management could double the main grain yields in SSA. Whilst other studies have dwelt on soil nutrients as the major solution to low yields in SSA (Sanchez 2002, Raimi, Adeleke et al. 2017).

However, both rain and soil nutrients are important twin resources for small-holder farmers in Kenya and other ASAL areas. The productivity of better rain can be curtailed by limited soil nutrients. Limitations of soil nutrients can reduce RUE. Likewise, variability of rainfall affects the effectiveness of nutrient input. All-inclusive approach to the utilization of variable rain and available soil nutrients is essential.

2.4 Nutrients use for agricultural production

Nitrogen (N), Phosphorous (P) and Potassium (K) are the paramount nutrients for food production and at the same time, they are the most limiting nutrients. Universally, mineral fertilizer is regarded to be the main source of nitrogen, phosphorous and potassium. The developed economies invest in mineral fertilizer to retain soil fertility and sustain profitable production systems. However, these nutrients (N, P and K) are limiting partly due to economic cost, and have reduced potential food production in the developing countries.

In Africa, the limitation of these nutrients is of continental concern. In the year 2006, African leaders met in Abuja, Nigeria, and agreed to lobby for increased use of mineral fertilizer to 50 kg per hectare per season, specifically for SSA (Declaration 2006, Tittonell, van Wijk et al. 2009). This was agreed in order to achieve African green revolution. However, the available reports afterward, show that mineral fertilizer use hardly exceeds 10 kg per hectare per season, in SSA (Morris, Kelly et al. 2007, Vanlauwe, Kihara et al. 2011, Jayne and Rashid 2013) (Table 2-1).

Table 2-1: Utilization of mineral fertilizer and crops production in SSA countries

Fertilizer consumption and maize production in different countries			Beans production in different countries	
Countries	Fertilizer consumption: Average (kg/ha)	Maize production: Average grain yield (kg/ha)	Countries	Beans production: Average grain yield (kg/ha)
Kenya	29	1564	Kenya	520
Ethiopia	13	1744	Kenya	820
Uganda	1	1781	Kenya	380
Nigeria	6	1090	Tanzania	2580
Burkina Faso	3	1768	Tanzania	1940
Ghana	4	1421	Tanzania	1830
Malawi	39	1296	Zambia	1660
Mozambique	5	898	Zambia	380
Zambia	8	1454	Zambia	590
Zimbabwe	43	1022	Mozambique	540

(Sanginga and Woomer 2009, Kaizzi, Cyamweshi et al. 2018)

The factors contributing to underutilization of mineral fertilizer in SSA include the following: a) Low profitability, b) Farmers lacking adequate knowledge on importance and use of mineral fertilizer, c) Mineral fertilizer packed in minimum of 50 kg, locking out resource-constrained farmers willing to buy low package of fertilizers, d) Lack of input credits, e) Unresponsive fertilizer policies, F) Lack of affordability due to high fertilizer prices (Chianu, Chianu et al. 2012). In Western Kenya, cost is the main deterrent to the use of mineral fertilizer, and also other factors include fear of adulteration of mineral fertilizers and limited technical knowledge (Misiko, Tittonell et al. 2011).

Whilst African leaders are lobbying for increased use of mineral fertilizer, the downside of it has also been reported. Long term field experiment in Kenya has shown reducing maize yields with increase in use of mineral fertilizer (Nandwa and Bekunda 1998). Also, lower maize yields with intensive use of mineral fertilizer has been reported in Zimbabwe (Waddington, Mekuria et al. 2007). In Nigeria, it has also been shown that continuous maize fertilization with mineral fertilizer could not sustain yields over 16 years (Vanlauwe, Diels et al. 2005).

The potential reasons leading to negative relationships between mineral fertilization and crop yields include soil deficiency in essential micro-nutrients and unbalanced nutrition. Ayeni and Adetunji, 2010, showed that the combination of NPK fertilizer with the poultry manure increased availability of micro-nutrients, Fe, Zn, Mg, Cu and Mn, thereby maintaining balanced nutrition, and increasing maize yield than the case of NPK fertilization alone. Also, farm management practices including weed control, pests and disease management, influences the efficacy of mineral fertilizer. In the rain-fed production systems of Africa, dry spells over period of crop development can contribute to low yields despite investment in mineral fertilizer (Kamanga, C.G. et al., 2014).

Additionally, some work in SSA has reported advantages of organic fertilization than mineral fertilizer. In Burkina Faso, more beneficial evapotranspiration was found in compost manuring than in mineral fertilization (Zougmoré, Mando et al. 2004). 25 out of 40 farmers in Western Kenya, linked *Striga* infestation with mineral fertilizers and believed that manure reduces prevalence of *Striga* weed (Misiko, Tittonell et al. 2011). Also, application of organic fertilizer produced double grain yield than the yield obtained with mineral fertilization (Affholder 1997). This is attributable to ability of organic fertilizer to enrich carbon and feed soil biota (Sánchez 2010).

Contrarily, even though SSA leaders are making common recommendation on mineral fertilizer input, the variability of agricultural land in space including soil types, rainfall pattern and management aspects, does not allow blanket fertilizer utilization for SSA agriculture. In addition, uniform recommendation of fertilizer input without consideration of profitability is incomplete. Therefore, it is conceivable to pursue other options for soil fertilization from local resources before thinking of mineral fertilizer for small-holder and resource-constrained farmers.

Livestock manure is available and affordable source of fertilization for low-external input systems of SSA. The importance of manure has been embraced globally, where 34 million tonnes of N, 8.8 million tonnes of P and 22.9 million tonnes of K were reported to be recovered from manure in the year 1996 (Sheldrick, Syers et al. 2003). Additionally, a study in West Africa reported that 100% of farmers indicated the importance of manure for soil fertilization while only 56% mentioned mineral fertilizer, depicting the importance of livestock manure in the food production systems of SSA (Fofana et al 2012).

However, the nutrient value of livestock manure is still underutilized and the insignificant use of livestock manure is a problem in some parts of SSA (Harris and Yusuf 2001, Harris 2002). Also, the utilization of livestock manure is affected by its management, logistics of collection, and the spatio-temporal variability of agricultural environment of SSA.

2.4.1 Nutrient balance

A robust measure is required to monitor the sustainability of low-external input systems. The food production systems in Marsabit-central, and other similar environment of SSA requires an indicator to monitor its sustainability. Nutrient balance is one potential measure that can be used to monitor the production systems of Marsabit-central farms.

Nutrient balance is the difference between the total nutrient output and the total nutrient input, and can be source of guidance to farmers and policy makers. Nutrient balance is an important agri-environmental indicator. It is crucial to know the nutrient balance of the crop fields before deciding to use fertilizer input. This is to avoid degradation of the environment. Negative nutrient balance indicates over-mining of nutrients and can lead to food insecurity and deteriorating environment.

Highly positive nutrient balance can lead to environmental problems like seepage, leaching, eutrophication and contribution to greenhouse gases through nitrification and denitrification processes. If zero balance (equal measure of nutrient inputs and nutrient outputs) is maintained in the production systems, it is the desired nutrient balance. However, balanced nutrients is mainly seen in the natural environment like forests and intact grazing lands, but hardly seen in crop or livestock systems.

Nutrient balance in Sub Saharan Africa

Depletion of nutrient occurs when more nutrients are mined from production system than the quantity of nutrient input, resulting in negative nutrient balance. The levels of nutrient balance in Sub Saharan Africa ranges from low depletion to very high depletion (Table 2-2).

Table 2-2: Levels of nutrient balance in SSA

Rate of depletion	Nitrogen depletion (kg/ha)	Phosphorous depletion (kg/ha)	Potassium depletion (kg/ha)
Low	<10	<1.7	<8.3
Moderate	10 to 20	1.7 to 3.5	8.3 to 16.6
High	20 to 40	3.5 to 6.6	16.6 to 33.2
Very high	≥40	≥6.6	≥33.2

(Stoorvogel and Smaling 1990, Smaling, Nandwa et al. 1997)

Over the last three decades, most of the reviewed literature indicates negative nutrient balance across Sub-Saharan Africa. In the year 2000, the nutrient balance in SSA was predicted at -26 kg/ha, -7 kg/ha and -23 kg/ha for nitrogen, phosphorous and potassium, respectively (Stoorvogel, Smaling et al. 1993). Likewise, nutrient balance of -68 kg/ha, -10 kg/ha, and -61 kg/ha for nitrogen, phosphorous and potassium, respectively, have also been shown (Smaling, Stoorvogel et al. 1993, de Jager, Kariuku et al. 1998, Shepherd and Soule 1998, Van den Bosch, Gitari et al. 1998, Esilaba, Nyende et al. 2005, Gachimbi, van Keulen et al. 2005).

The negative nutrient balance is more intense in East Africa, followed by coastal West Africa and Southern Africa, but less a problem in central Africa (Smaling, Nandwa et al. 1997). The severity of nutrient balance depends on the soil types, levels of soil fertilization and the rate of nutrient mining.

Crops grain and crops non-food biomass are the main sources of nutrient outflows contributing to the nutrients depletion in SSA. Negative nutrient balance in SSA is also attributable to minimal use of mineral fertilizer and also application of manure less than the crop nutrient uptake.

Nutrient balance in Kenya

In Kenya, cases of negative nutrient balance have been shown. For example, nitrogen flows is dominated by negative balance of up to -159.00 kg/ha, phosphorous balance ranged from -15.00 to 25.00 kg/ha, and potassium balance ranged from 18 to -82 kg/ha (Table 2-3) (Sheldrick, Syers et al. 2002). Based on the published work of nutrient balance in Kenya, timely investment in nutrient management need to be a priority. Ecological sustainability can be maintained by adding equal measure of nutrients removed to the production systems each year or season nutrients are extracted through food grains and non-food crop biomass. This can deter excessive withdrawal of nutrients and stabilize the nutrient balance.

Table 2-3: Nutrient balance reported in Kenya

Year of study	Scale of study	Nutrient balance (Kg/ha)			Sources
		N	P	K	
1988	National	-15.70	-1.90	-19.30	(Sheldrick and Lingard 2004)
1998	National	-16.20	-1.50	-20.10	(Sheldrick and Lingard 2004)
1982-84	National	-42.00	-3.00	-29.00	(Stoorvogel, Smaling et al. 1993)
2000	National	-46.00	-1.00	-36.00	(Stoorvogel, Smaling et al. 1993)
2004	District	-96.00	-15.00	-33.00	(FAO, 2004) (Chianu, Chianu et al. 2012)
2002	District	+1.10	-1.70	-5.40	(Onduru and Du Preez 2007)
1995-96	District	-102.00	-2.00	-34.00	(de Jager, Kariuku et al. 1998)
1995-96	District	-72.00	-4.00	+18.00	(de Jager, Kariuku et al. 1998)
1995-96	District	-55.00	+9.00	-15.00	(de Jager, Kariuku et al. 1998)
1998	District	-40.5	-2.55	-	(Shepherd and Soule 1998)
1998	District	-71.00	+3.00	-9.00	(Van den Bosch, Gitari et al. 1998)

Table 2-3 ……continued

Year of study	Scale of study	Nutrient balance (Kg/ha)			Sources
		N	P	K	
1996	District	-107.00	-8.00	-	(Shepherd, Ohlsson et al. 1996)
1993	District	-112.00	-3.00	-70.00	(Smaling, Stoorvogel et al. 1993)
2013	Farm	-3.00	-	-	(Tully, Wood et al. 2015, Tully, Wood et al. 2015)
1999	farm	-9.40	+0.30	-0.70	(Gachimbi, van Keulen et al. 2005)
1999	farm	-4.90	-0.30	-3.40	(Gachimbi, van Keulen et al. 2005)
1999	Farm	-5.00	+0.40	+0.60	(Gachimbi, van Keulen et al. 2005)
1996	Farm	-50.67	-5.33	-82.67	(Lehmann, Weigl et al. 1999)
nm	Farm	+18.00 to -50.00	+7.00 to +28.00	-	(Onduru, Diop et al. 2002)
nm	Farm	-13.00 to -159.00	-4.00 to +25.00	-	(Onduru, Diop et al. 2002)

nm means that year of study not mentioned in the publication.

The possible reasons resulting to differences in nutrient balance include the following: a) Scale of nutrient modelling. Use of national-level data for nutrient modelling falls short of considering spatio-temporal variability of food production systems, while the nutrient balance at the level of crop field considers the field-specific farming environment. This results in variable nutrient balance. Onduru and Preez 2007, reported high nutrient balance at macro-scale and lower nutrient balance at the scale of farm. b) Level of fertilizer inputs. Less fertilizer input results in more negative nutrient balance than higher case of field fertilization. In Kenya and other SSA countries, less resource-endowed farmers put lower amount of fertilizer to crop fields. Positive correlation between number of TLUs and nutrient balance has been reported in Kenya. This is due to importance of livestock in providing manure for fertilization of crop fields (Onduru and Preez, 2007). Onduru, Diop et al. 2002, also showed the less net negative nitrogen balance with application of liquid manure. This study also reported more negative nitrogen balance of -13 to -159 kg/ha/yr in high potential areas and less negative nitrogen balance of +18 to -50 kg/ha/yr in low potential areas. High potential areas involve areas with better soil fertility and reliable rainfall while low potential areas are characterized by poor soils and variable rainfall pattern. c) Level of nutrient outflows. Higher nutrient outflows through crop harvests, erosion, leaching and other pathways of nutrient outflows results in more negative nutrient balance than the case of less nutrient outflows.

2.4.2 Partial and full nutrient balance

Nitrogen (N), Phosphorous (P) and Potassium (K) are the most common nutrients calculated in the study of nutrient balance. Previous studies have classified nutrient balance into two groups (Wijnhoud, Konboon et al. 2003, Haileslassie, Priess et al. 2007). Partial nutrient balance is calculated by subtracting aggregate of two primary outputs (crop grains and non-food crop biomass) from aggregate of two primary inputs (mineral fertilizer and manure). Full nutrient balance is calculated by subtracting aggregate of five nutrient outputs (crop grains, non-food crop biomass, leaching, denitrification and volatilization and erosion) from aggregate of five nutrient inputs (mineral fertilizer, manure, atmospheric deposition, biological N fixation and sedimentation) (Stoorvogel, Smaling et al. 1993, Sheldrick and Lingard 2004). Both partial and full nutrient balance are important sustainability indicators in food production systems. Comparatively, partial nutrient balance is easily quantifiable and can be used by farmers, without much involvedness.

However, there are gaps in the previous studies on nutrient balance of SSA. One is that, some of the studies used national statistics and assumed country-based uniformity in nutrient inputs and nutrient outputs. The in-country variability in space and time has marginally been considered in reported studies on nutrient balance. Further, studies on nutrient balance used cropping intensity to determine whether there is cropping activity in the area of interest. Some farming environment of small-holder crop-livestock systems was regarded as pure livestock producers or pastoral systems. This has likely left out some arable areas, like mountain areas of arid and semi-arid lands of SSA. Therefore, calculating inputs and outputs for nutrient balance need to be site specific, and also need to consider spatio-temporal variability of agricultural environment.

2.5 Crop-livestock integration

Crop-livestock systems is the back-bone of food production in SSA. Mixed crop-livestock systems produce over 50% of world meat and over 90% of milk in developing countries (Thornton and Herrero 2001). It involves interdependency among crop and livestock subsystems and it offers an opportunity for a win-win situation where the crop and livestock subsystems benefit each other. Integrated crop-livestock systems has a potential to reverse the trend of negative nutrient balance.

In mixed crop-livestock systems, the productivity of variable rain and available manure can be enhanced through integrative approach. The crop-livestock systems can be sustainably intensified by optimising its interactions.

The key interactions in crop-livestock systems include the following:

1. Provision of draft power – Animals including oxen, camel and donkey provides power for cultivation of farm, transportation of crop grains and non-food crop biomass, and watering of animals (Steinfeld, de Haan et al. 1998).

2. Feeding – crop non-food biomass, weeds, thinnings are sources of livestock feed. In some places, they are the major source of feeds during the late dry seasons and drought period (Herrero, Thornton et al. 2010) (Valbuena, Erenstein et al. 2012).

3. Cash flows – Income from one subsystem can be reinvested in another subsystem. In Southern Zimbabwe, women sell goats to purchase inputs for their crop subsystem (Homann, Van Rooyen et al. 2007).

4. Livestock manure – Livestock manure is an important source of nutrients and builds soil organic matter. It is estimated that over 20% of the nitrogen for crop production in mixed systems come from livestock (Liu, You et al. 2010). Crop-livestock integration systems transfer nutrients within the food production environment (Rufino 2008). Fofana, Zida et al. (2012), reported positive relationships between livestock ownership, manure availability and crop production.

Crop-livestock systems can provide integrative solutions to food security in SSA. Increasing the linkages and interdependencies among the crop and livestock subsystems is the gateway to sustainable food production in small-holder farming system of SSA.

In Sub Saharan Africa, farmers have been benefiting from multiple effects of this integrated systems. In north western Nigeria, the by- products from crop farming i.e. crops residues and livestock by-products i.e. manure are commercialized. The farmers buy manure from transhumant herders in exchange for crop residues (Williams, Powell et al. 1995) (Powell, Fernandez-Rivera et al. 1996). Crop residues are low cost feed resource and are major source of nutrients for livestock in developing countries.

The integration of crop-livestock systems provide diversified sources of livelihood and also optimally use the variable environment. Crop non-food biomass is an important source of livestock feed. Also, livestock do straight manuring while feeding directly on non-food crop biomass after harvest. Additionally, livestock manure is the affordable and available nutrient input for resource-constrained and small-holder farmers. Therefore, research efforts focusing on sustainable management of crop-livestock systems is necessary, especially with increasing human population and climate variability in SSA.

Nevertheless, while the research on crop-livestock integration in SSA has been pursued, the consideration of variability within the crop fields and grazing lands has remained elusive. For example, it has been acknowledged that collection of manure from home-based livestock may not be sufficient for field's fertilization (Fofana, Zida et al. 2012). However, manure production from the near and distant grazing lands is important but it is underexplored component of crop-livestock systems.

Generally, the complexity of crop-livestock systems in SSA has blurred the clear understanding and the quantification of beneficial crop-livestock interactions. Notably, the changeability of collectable manure with space and time is still less understood.

2.5.1 Scenario analysis

Crop-livestock systems is complex and operates in variable environment. It requires understanding of various factors to comprehensively study crop-livestock systems. Although efforts have been made on modelling the crop-livestock systems in SSA, blanket use of national statistics is common (Rufino, Brandt et al. 2014). Scarcity of data has resulted in use of vague national data for continental and sub-national level modelling.

Crop-livestock system is weather-dependent and modelling needs to cater for vagaries of weather. Furthermore, the biophysical conditions, including soil status are site specific. The crop-livestock environment in SSA is spatially and temporally variable. Modelling approaches that considers this variable environment are essential.

Considering the complexity of crop-livestock systems in SSA and variability of environment in which it operates, system analysis is more relevant than modelling single subsystem within the broader crop-livestock systems. System analysis enables understanding of interlinkages within the crop-livestock system. Recent work has also embraced system analysis than solely focused study within the broader production systems of SSA (Giller, Tittonell et al. 2011).

System analysis considers various scenarios that depicts the variable environment in which the crop-livestock production of SSA operates. This analysis examines possible implications of alternative strategies for improving crop-livestock production (De Fraiture and Wichelns 2010). It offers opportunity to explore diverse mechanisms and provide options to crop-livestock farmers. This is necessary as there cannot be a specific blue-print of ways for sustainable food production. Thus, basket of options can be generated from scenario analysis of crop-livestock production systems.

2.6 Research gaps

The following are the gaps in the existing knowledge:

Marsabit-central Sub-county is remotely located and has received little attention with regard to land-based production. The map on land use classes provide information on the current land-based activities and also offers point of future reference. There is no documentation on Marsabit-central land use map.

In addition, Marsabit-central sub-County is located within arid and semi-arid environment. Arid and semi-arid areas have variable climatic pattern, and this influences biomass production. Nevertheless, the spatial and temporal heterogeneity of rainfall and its influence on production of forage biomass in Marsabit-central is less understood.

Soil nutrient is an important resource for food and biomass production. In ASAL areas of Kenya, the study on soil nutrient concentrations is not conclusive. Additionally, modelling of nutrient balance within ASAL areas of SSA, mainly used coarse national level data. The possible reason contributing to high variability of nutrient balance in Kenya and other SSA countries is use of coarse national-level data, with less consideration of continuously-variable food production systems.

Owing to complexity, the improvement of crop-livestock integration require systems approach. The existing work dwelt on isolated studies working on performances of various subsystems within the complex crop-livestock integrated systems. System analysis of crop-livestock integration based on the consideration of variable environment contributes to nutrient modelling knowledge in arid and semi-arid environment of SSA.

Chapter 3 : Land use classification and land productivity

3.1 Introduction

Remotely sensed data can be useful in areas where spatial and temporal first-hand data are limited. Marsabit County situated within ASAL areas of northern Kenya is vast and also remotely located. The utilization of Marsabit-central landmass is prone to change owing to climate variability and growing human population.

The information on land use classes and land productivity in Marsabit-central is scanty. Use of remotely sensed data and GIS tools can provide further insights on the land use classes and status of land productivity (Shalaby and Tateishi 2007). NDVI provides indication of land productivity. It is recognized as a robust approach of estimating green biomass, providing measure of primary land productivity (Wang, Price et al. 2001). NDVI can be used to monitor the aboveground biomass production in Marsabit-central.

In Marsabit-central, the human and livestock population are natural resource-dependant. The people uses natural biomass for feeding their livestock and they are also practising small-scale crop agriculture. Therefore, NDVI can provide proxy measure of food and feed availability in Marsabit-central.

> This chapter addresses objective 1: *To reveal the main land use classes in Marsabit-central sub-county*

The chapter seeks to:

i. Show different land use classes in Marsabit-central.
ii. Identify the NDVI in various land use classes.

3.2 Methods of study

The method of analysis involves acquisition of Landsat imagery, and processing the imagery before further analysis. After processing of the Landsat imagery, different land use classes are identified and also NDVI is computed (Figure 3-1).

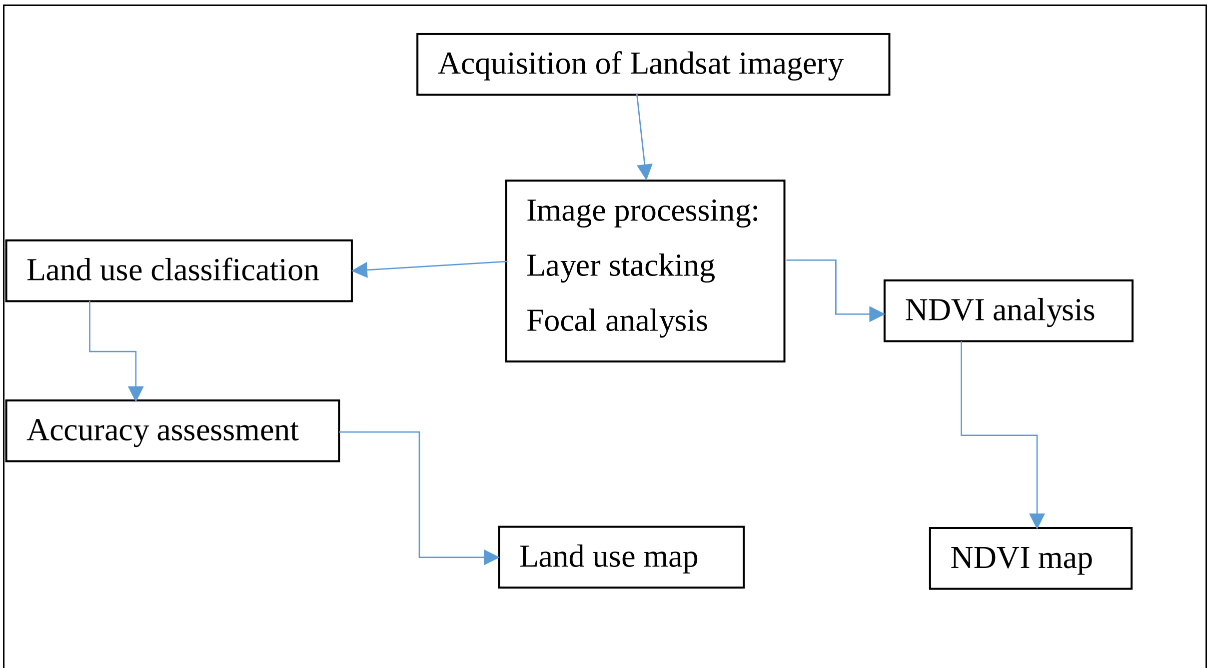


Figure 3-1: Flow chart on method of analysis

3.2.1 Remotely sensed data

Acquiring of Landsat imagery

The Landsat imagery data was downloaded from USGS website (https://earthexplorer.usgs.gov/). Landsat 7 ETM+ (Enhanced Thematic Mapper Plus) was used for this work. Bands 1, 2, 3, 4, 5 and 7 of the Landsat data were acquired (Table 3-1). The Landsat data acquired has a resolution of 30 m * 30 m. The data was then processed before further analysis.

Table 3-1: Characteristics of the bands

Bands number	Wavelength (μm)	Names
1	0.45-0.52	Blue
2	0.52-0.60	Green
3	0.63-0.69	Red
4	0.77-0.90	Near Infrared
5	1.55-1.75	Short-wave Infrared
7	2.09-2.35	Short-wave Infrared

Processing of the Landsat data

The Landsat imagery data had stripes due to the failure of the Scan Line Corrector (SLC) on 31st May 2003, and this reduces the quality of the output. This demands processing of the image before analysis. Processing involved layer stacking and focal analysis, using Erdas Imagine, v 2014. The image of different bands were layer stacked in Erdas Imagine, v 2014. This resulted in one image with layer of bands. The layer stacked image was further subjected to focal analysis. The focal analysis removed the stripes from the Landsat image. In each round of the focal analysis, the immediate former that went through focal analysis window becomes the input image. After six rounds of focal analysis, the Landsat image was suitably destriped, and could be used for land use classification and computation of NDVI.

3.2.2 Land use classification

Erdas Imagine, v 2014, was used to classify the existing land uses in the study area. Supervised classification method was employed. Supervised classification is a user-guided method of classification. The maximum likelihood classifier is one option in the supervised classification system of Erdas Imagine, v 2014, and this option was used (Long and Srihann 2004).

The supervised classification method requires the user to have a prior knowledge or to have done ground-truthing of certain areas in the field. The number and the types of land use classes were determined by the user, based on the previous knowledge of the place and also from the empirical field work. Therefore, the classification scheme included the following: forest, crop fields, good grazing lands, poor grazing lands and urban or settlements.

The signature editor was used to identify these different known or "training" areas for each class of land use. Polygons were created around each training area and added to the signature editor. For each class type, training area was sampled 12 times and added to the signature editor. The 12 subclasses (training areas) were merged in the signature editor and this resulted in one type of land-use class. A single signature file containing different land use classes was produced and saved.

This was followed by supervised classification of the entire landscape, using the signature file as the input data, so that, areas other than the training areas could be assigned to one of the land use classes. The supervised classes were assigned different colours, with each colour representing different land use classes. The land use classes are displayed in form of a map.

In addition, the map composition function of Erdas Imagine, v 2014, was used to add the properties of land use map. These properties include: map frame, scale of the map, as well as the compass direction.

Accuracy assessment of supervised classes

After supervised classification, the classes were assessed to find if each group was classified correctly. This involved identifying the percentage of pixels in the original training areas that were correctly classified versus the pixels misclassified. The contingency type of accuracy assessment was applied. This resulted in contingency table of error matrix showing accuracy level in percentages.

Variability of land use classes with space

Pixel-based data on land use classes was generated for entire landscape (study area). This is followed by sampling land use classes at interval of 1.0 km along the Eastings of land use map and at interval of 0.5 km across the northings of land use map. The pixel-based land use classes were sampled for about 22.0 km transect along the Easting, covering about 80% of the study distance. At every single km along the 22.0 km transect, the type of land use class was identified for 47 pixels. Variability of land use classes from upper home fields to lower grazing lands is shown in graphical format.

3.2.3 Ground-truthing of the land use classes

Ground-truthing was conducted both during the long season of 2016 and the season of 2017. It was carried out on high altitude areas of crop lands and also within the lower adjacent areas of grazing lands.

Ground-truthing involves the researcher visiting various sites and ascertaining the land-use classes. During ground-truthing, GPS machine was used to record geographical positions in the study sites. Each site represents different land use class. The area of study has about four administrative locations. In the crop fields, 3 farms in each of the four locations were selected. Maize and bean plots were randomly selected and their GPS locations were recorded. 12 crop fields were ascertained and geo-referenced. In the good and poor grazing lands, researcher stand in the middle of grazing site and identify one direction randomly, the researcher then moves 200 m in the direction identified and records GPS points. 12 good grazing sites and 12 poor grazing sites were geo-referenced. In addition, 12 accessible points in the forest area were identified and their GPS locations recorded. Likewise, the GPS locations of urban centre and the home of farmers in the crop-fields studied were taken. Afterwards, the ground-truthed land use classes were compared with the different land use classes computed with Erdas Imagine, v 2014.

3.2.4 Assessing the land productivity

Normalized Difference Vegetation Index (NDVI)

NDVI is a proxy measure of land productivity (Tucker, Slayback et al. 2001). NDVI was computed for the long seasons of 2016 and 2017, from the Landsat image captured on 26th July 2016 and 26th May 2017, respectively.

NDVI was calculated using Erdas Imagine, v 2014, and it was computed from the image processed through focal analysis window of Erdas Imagine, v 2014. The final output image after sixth round of focal analysis was used as the input data for processing NDVI.

NDVI was computed using the formulae below:

$$NDVI = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

Where RED and NIR stand for the spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively.

Variability of NDVI from upper areas to lower grazing lands

To understand the variability of NDVI with space, 22 km transect assessment was run 9 times. 22 km transect was used because it provided the largest range, covering about 80% of the study distance, but was short enough to avoid edge effects. The transects were arranged regularly on a grid across the landscape (study area). The beginning and end of the transect ranged from 37.97 Easting, 2.22 Northing to 38.16 Easting, 2.39 Northing (Table 3-2).

Table 3-2: The beginning and end of the transects

Transects	Beginning of the transect		End of the transect	
	Easting (dd)	Northing (dd)	Easting (dd)	Northing (dd)
1	37.97	2.22	38.16	2.22
2	37.97	2.24	38.16	2.24
3	37.97	2.26	38.16	2.26
4	37.97	2.28	38.16	2.28
5	37.97	2.30	38.16	2.30
6	37.97	2.32	38.16	2.32
7	37.97	2.35	38.16	2.35
8	37.97	2.37	38.16	2.37
9	37.97	2.39	38.16	2.39

The transects were run for the long season of 2016 and the long season of 2017. The NDVI values across the 9 transects were averaged. One composite transect of 0-22 km distance was identified for the long season of 2016 and also one composite transect for the long season of 2017. The transects of both seasons show the variability of NDVI values from the upper high altitude areas to the lower grazing lands.

In addition, NDVI values were identified in the geo-referenced areas used for ground-truthing of land use classes: forest, the crop fields, good grazing lands and the poor grazing lands. The NDVI values in these land use classes were compared.

3.3 Results

3.3.1 Land-use classes

The important land use classes purposely used for food and feed production are the crop fields and the grazing lands. Maize and beans are the dominant food crops. Good grazing lands are mainly found on high altitude areas close to the crop fields, while poor grazing lands are located at further low altitude areas (Table 3-3 and Figure 3-2).

Table 3-3: Land use classes

Land use classes	Description
Good grazing lands	This class involves natural pastures. Cattle which is the predominant livestock in the study area feeds on these pastures. Good grazing lands are found mainly in higher home fields but also in lowland areas.
Poor grazing lands	There are mainly found in lowlands, and are characterized by grasses, shrubs, bareness, patchiness and also has stones. This land use class is also used for livestock production.
Urban/settlements	These include market centres, town as well as homes.
Forest	There is one natural forest in the high altitude area and adjacent to the crop fields. It is also close to the urban centre. There are various tree sp in this forest, examples are *Prunus africanas* and *Croton megalocarpus.*
Crop fields	These are mainly maize and bean fields, and they are the dominant crops grown by the farmers, within the study area. Khat (*Catha edulis*) production is also practiced by some farmers, but it covers only about 8% of total crop fields (GoK, 2011a).
Clouds	There are clouds mainly concentrated around the forest and upper crop fields.

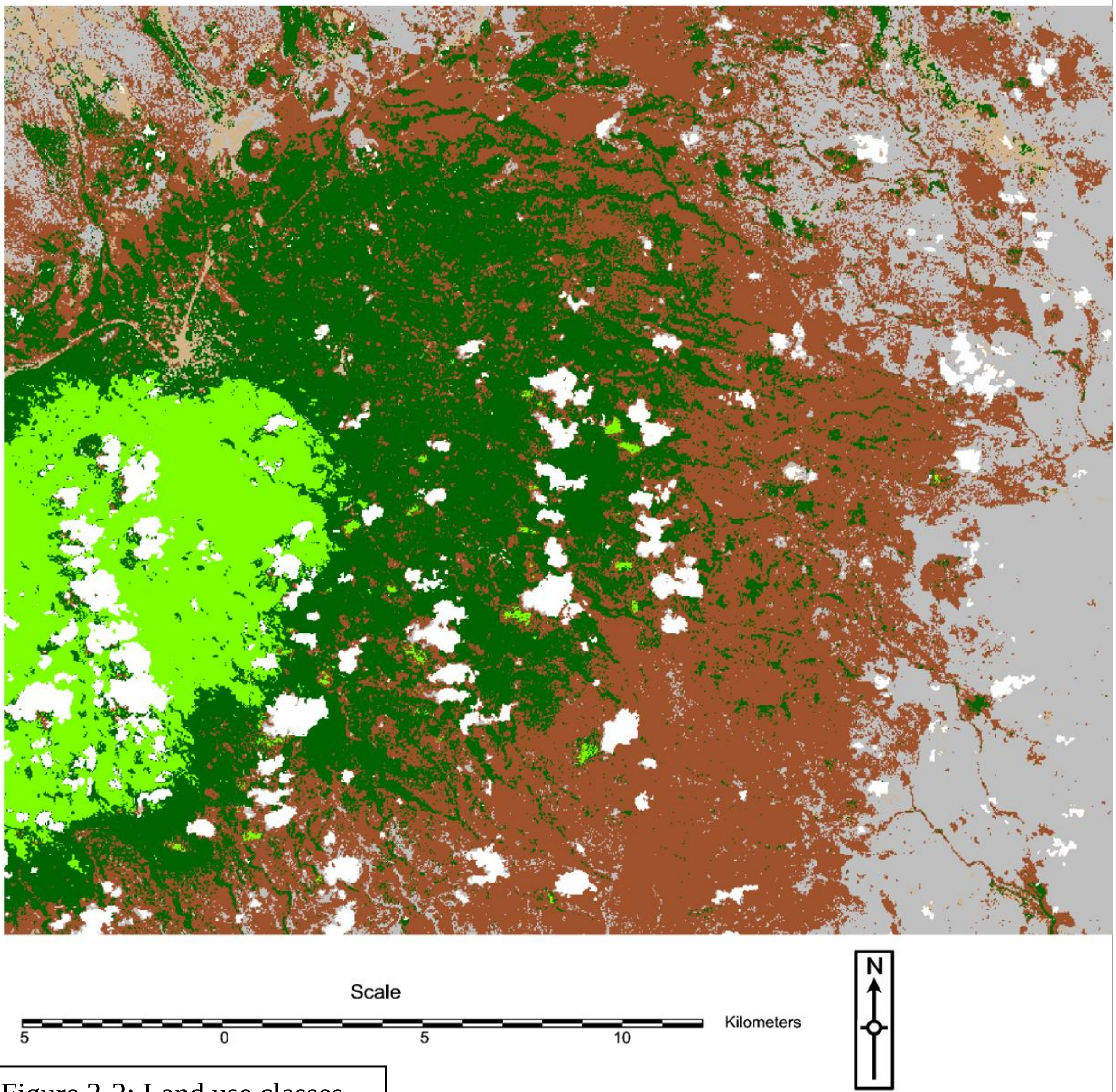


Figure 3-2: Land use classes

LEGEND

Good grazing lands	(brown)	Forest	(light green)
Poor grazing lands	(grey)	Crop fields	(dark green)
Urban/human settlements	(beige)	Clouds	

Accuracy assessment

The accuracy assessment revealed that 99% and 85% of pixels in the forest and crop fields, respectively, were classified correctly, showing high accuracy levels. Also settlements and good grazing lands have accuracy level over 85%. The accuracy level of poor grazing lands is 90%. Finally, the accuracy level of clouds is over 97%. Supervised classification method effectively classified the main land use classes in Marsabit-central Sub-County (Table 3-4).

Table 3-4: Contingency matrix of accuracy assessment: Image captured on 26th July 2016

Classified data	Reference data																		
	Forest			Crop fields			Urban/settlements			Good grazing lands			Poor grazing lands			Clouds			
Classes	Pixel count[1]	% Column	% Row	Pixel count	% Column	% Row	Pixel count	% Column	% Row	Pixel count	% Column	% Row	Pixel count	% Column	% Row	Pixel count	% Column	% Row	Total Row
Forest	5297	**99.36**	99.92	4	0.03	0.08	0	0	0	0	0	0	0	0	0	0	0	0	5301
Crop fields	29	0.54	0.25	10085	**84.56**	85.87	2	1.75	0.02	1608	9.17	13.69	20	0.21	0.17	0	0	0	11744
Urban /settlements	0	0	0	48	0.40	21.62	110	**96.49**	50.00	53	0.30	23.87	11	0.11	4.95	0	0	0	222
Good grazing lands	0	0	0	1774	14.87	9.93	2	1.75	0.01	15202	**86.71**	85.08	890	9.24	4.98	0	0	0	17868
Poor grazing lands	0	0	0	9	0.08	0.09	0	0	0	668	3.81	7.12	8709	**90.40**	92.79	0	0	0	9386
Clouds	5	0.09	0.67	7	0.06	0.94	0	0	0	0	0	0	4	0.04	0.54	729	**100**	97.85	745
Total column	5331			11927			114			17531			9634			729			45266

[1]The pixel size is 30 m * 30 m, as this is the resolution of original Landsat image used.

Variability of land use classes with space

In the upper home fields, the land use classes are dominated by forest, crop fields and good grazing lands. Moving further 17 km from upper home fields, the frequency of poor grazing land increases and take more space than other land use classes (Figure 3-3).

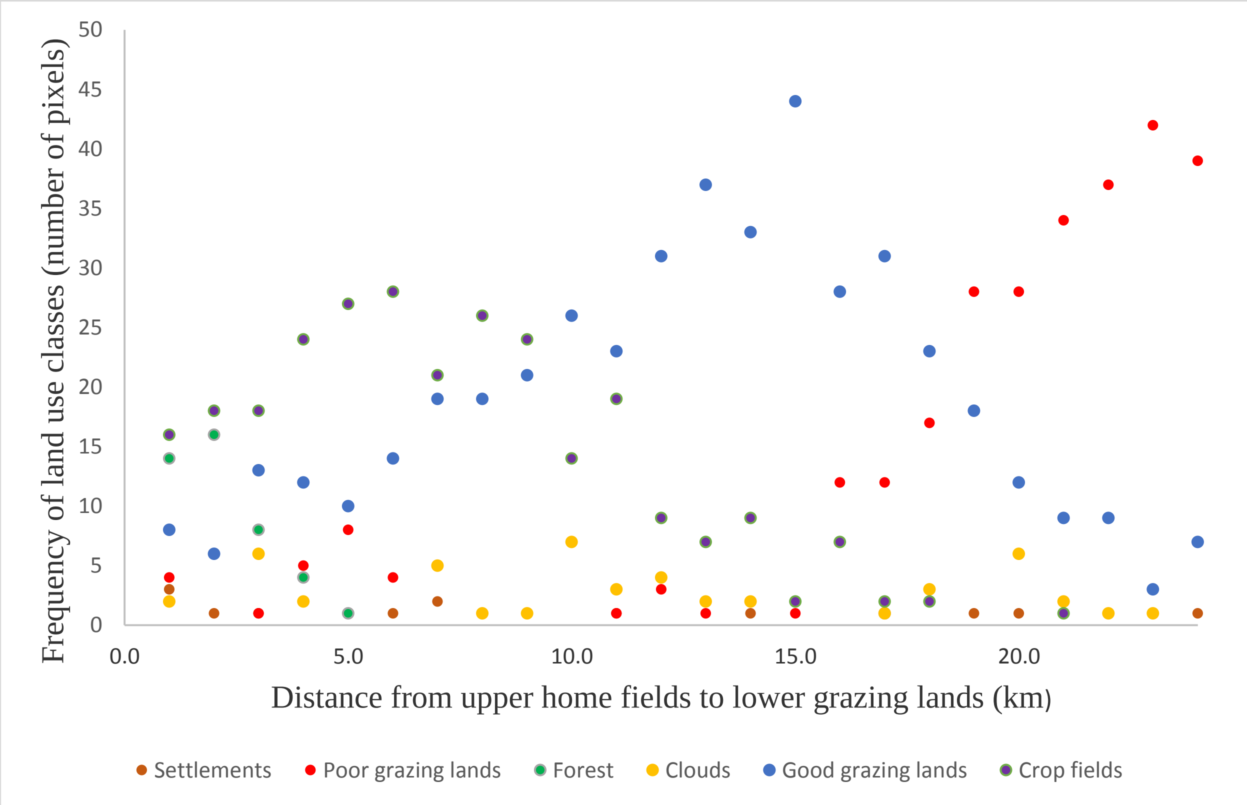


Figure 3-3: Variability of land use classes with space

The ground-truthed land use classes compare well with the land use classes determined through supervised classification. The ground-truthed areas of forest, urban/settlements and good grazing lands are all similarly classified by Erdas Imagine. Also, 60% and 75% of ground-truthed poor grazing lands and crop fields, respectively, conformed to the supervised classes of Erdas Imagine (Table 3-5).

Table 3-5: Ground-truthing of the supervised classes: Image captured on 26th July 2016

	Predicted						
	Land use classes	Forest	Crop fields	Urban/ settlements	Good grazing lands	Poor grazing lands	Row total
	Forest	12					12
Observed	Crop fields		9		2	1	12
	Urban/settlements			12			12
	Good grazing lands				12		12
	Poor grazing lands		2		3	7	12
	Column total	12	11	12	17	8	60

Digital Elevation Model

The altitude of the study area ranges from 491 - 1694 m asl. It has an interquartile range of 425 m asl. The altitude changes with different land use classes. Furthermore, the altitude oscillates around 600 – 800 m asl in the poor grazing lands, and 900 – 1300 m asl in the crop fields and good grazing lands. The maximum altitude is in the forested area (Figure 3-4 and Table 3-6).

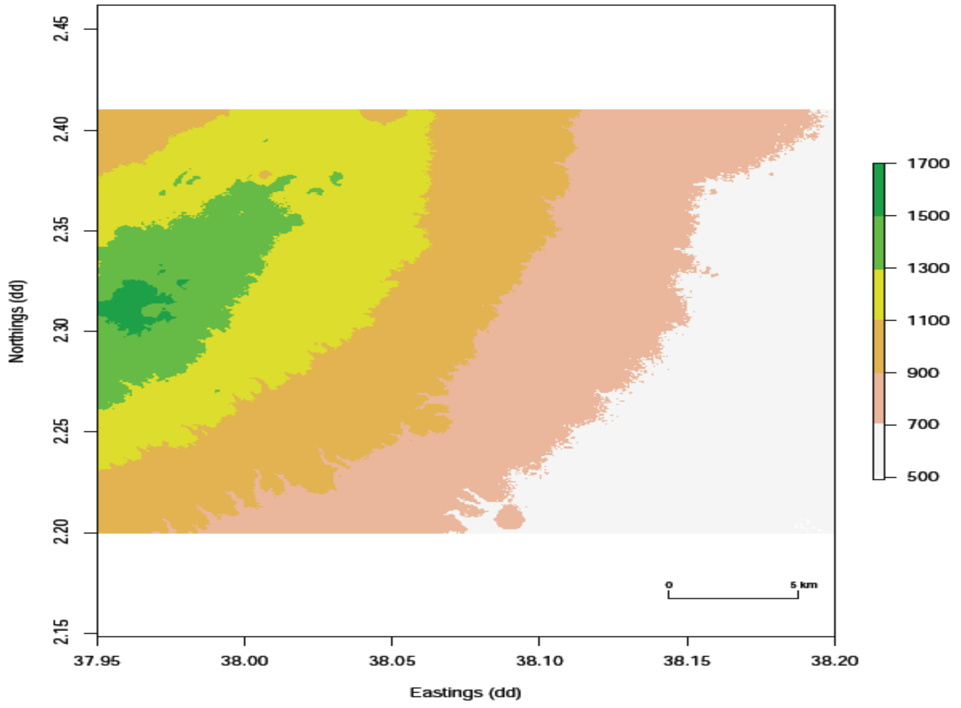


Figure 3-4: Digital Elevation Model (DEM) of the study area (m asl)

Table 3-6: Summary of Digital Elevation Model (DEM)

Statistics	Altitude (m asl)
Minimum	491
1st Quartile	700
Median	897
3rd Quartile	1125
Maximum	1694

3.3.2 Normalized Difference Vegetation Index

The source of the original images used for NDVI analysis are the Landsat images captured on 26th July 2016 and 26th May 2017, by USGS.

In the long rain season of 2016, NDVI ranged from -0.28 to 0.65 and in the long rain season of 2017, it ranged from -0.17 to 0.63 (Table 3-7) (Figures 3-5 and 3-6).

Table 3-7: NDVI for 2016 and 2017 long rain seasons

Statistics	NDVI 2016	NDVI 2017
Minimum	-0.28	-0.17
1st Quartile	0.02	-0.02
Median	0.07	0.04
3rd Quartile	0.17	0.18
Maximum	0.65	0.63

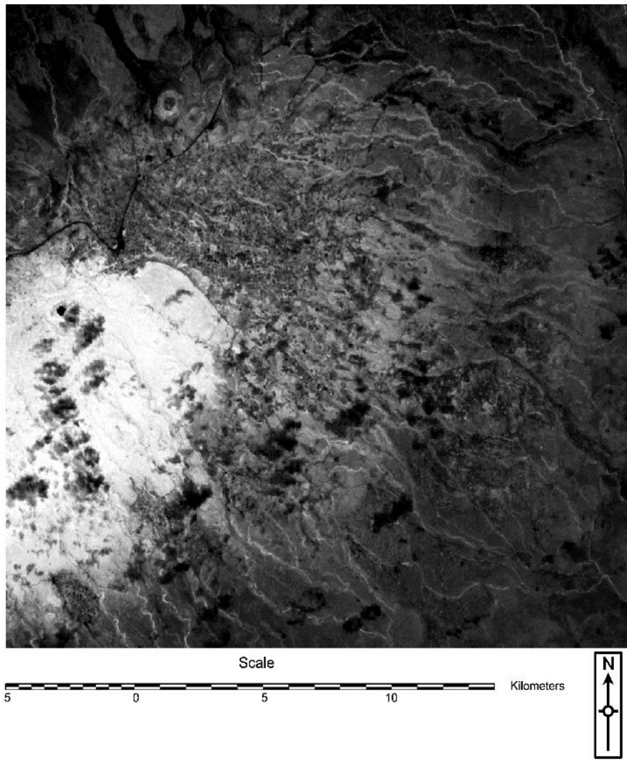


Figure 3-5: Normalized Difference Vegetation Index: Image captured on 26th July 2016

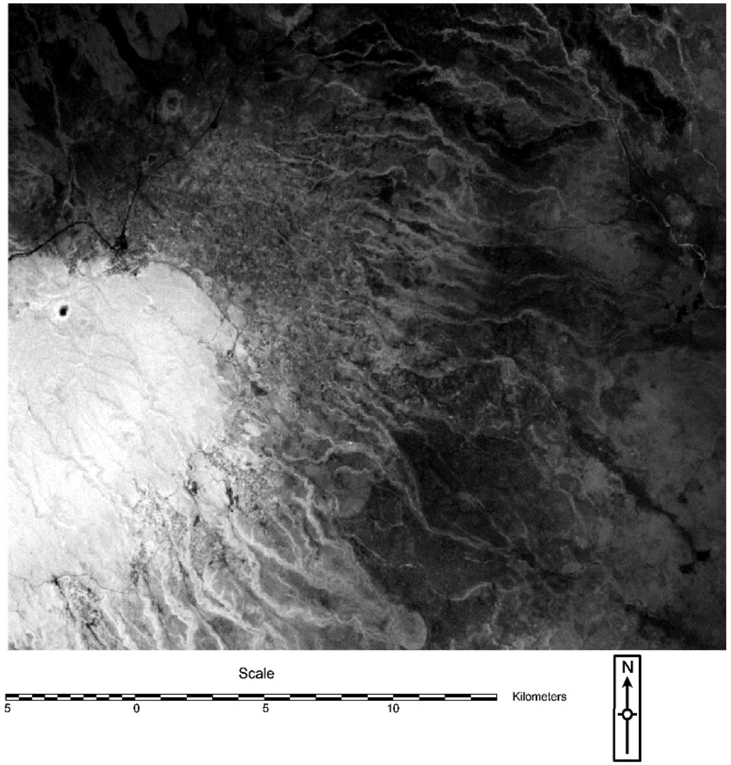


Figure 3-6: Normalized Difference Vegetation Index: Image captured on 26th May 2017

Colour	NDVI values	Colour	NDVI values
(White): High vegetation productivity	>0.3	(Dark grey): Low vegetation productivity	0.01-0.2
(Light grey): High vegetation productivity	0.2-0.3	(Black): zero vegetation productivity	<0.01

Variability of NDVI from upper home fields to lower grazing lands

The NDVI values reduce as it moves from upper areas to further away into the distant grazing lands. The upper areas of 0-3 km is dominated by forest and 4-15 km mainly involve crop fields and good grazing lands. The furthest areas from home fields are poor grazing lands. The lowest NDVI values are found in the poor grazing lands (Figure 3-7).

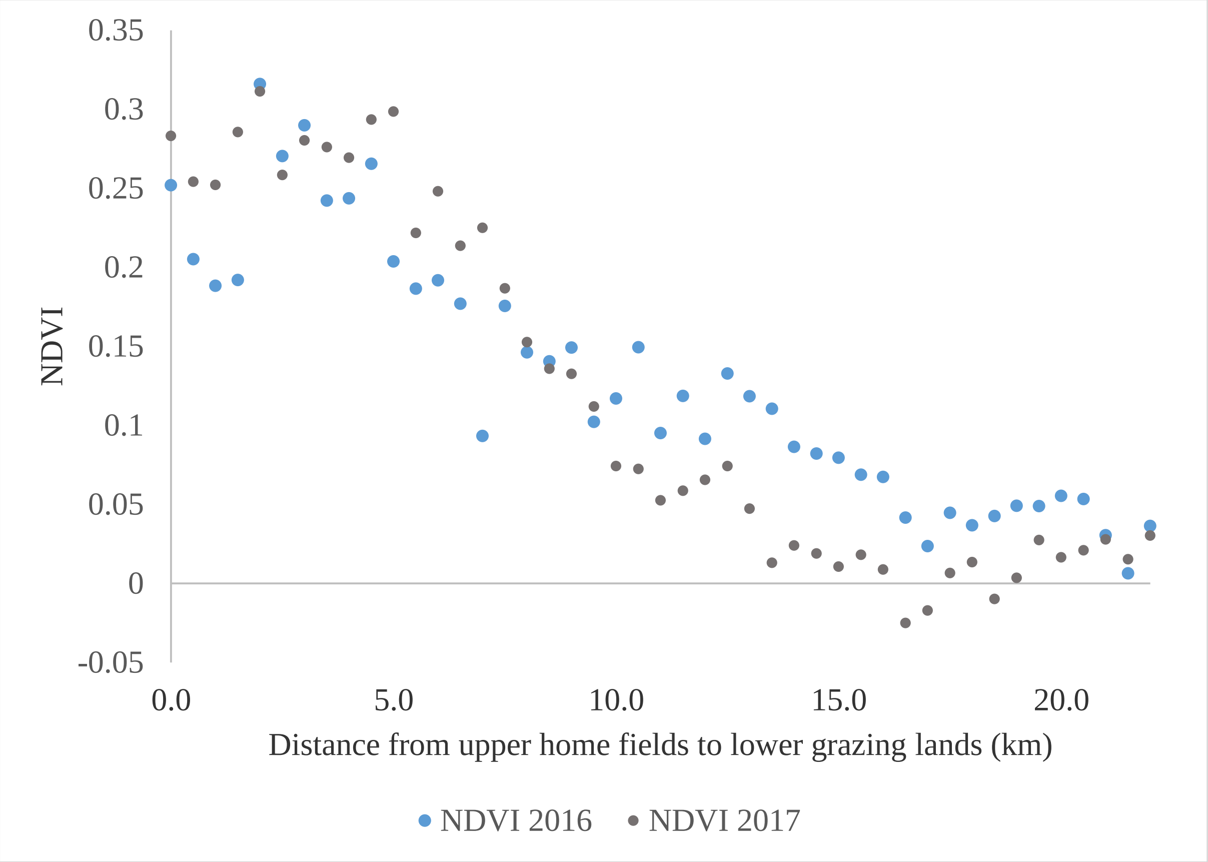


Figure 3-7: Normalized Difference Vegetation Index: Variability with space

Altitude and Normalized Difference Vegetation Index

NDVI increases with the increasing altitude. The forest has the highest altitude while the poor grazing lands are found on the lowest altitude zone. The good grazing lands are found close to the crop fields, and both have higher altitudes. NDVI differs significantly with the altitude and the land use classes ($P \leq 0.05$) (Table 3-8).

Table 3-8: Relationship between NDVI and Altitude (n=12)

Land use classes	Altitude (m asl) – Means and SE	NDVI 2016 Means and SE	NDVI 2017 Means and SE
Forest	1550.3(26.2)a	0.51(0.01)a	0.46(0.01)a
Crop fields	1145.0(50.0)b	0.16(0.02)b	0.23(0.04)b
Good grazing lands	1044.6(23.9)b	0.13(0.02)b	0.19(0.08)b
Poor grazing lands	718.3(43.5)c	0.05(0.02)c	0.03(0.01)c
Altitude effect *P* value ($P \leq 0.05$)		<0.001	<0.001
Land use class effect *P* value ($P \leq 0.05$)		<0.001	<0.001

Means in each column that do not share a letter are significantly different at $P \leq 0.05$, by Tukey's HSD test. Values are given as mean at each land-use class with SE in parentheses.

3.4 Discussion

The land use classes identified using Erdas Imagine compares well with the land use classes ascertained during the ground-truthing exercise. Crop fields are concentrated on high altitude areas while the vast lowland areas are used for livestock grazing (Figure 3-2).

Good grazing lands involve individual upper home fields set aside for natural pastures and also common grazing areas in the lower zone used for livestock production. Poor grazing lands are situated about >10 km from the crop-fields, on a lowest altitude zone. The livestock of farmers in high altitude areas utilize both the good and poor grazing lands. The existence of crop-fields and grazing lands in close proximity fits well the diversified livelihood systems. It promotes the interlinkages between the crop fields and the grazing lands. Crop-livestock integrated systems will remain the ideal food production system in the area of study.

Landuse classification is necessary in a dynamic production systems. Land use classes are subject to climate change, population growth and shifts in government policies. The arid and semi-arid areas of northern Kenya are historically known for pure pastoral production system. However, small-scale crop agriculture in mountain and other arable areas has also been adopted. Land use classification provides the policy makers, planners, scientists and other development partners with the opportunity for informed land-management decision. Also, NDVI give insights on the productivity of various land use classes.

The NDVI in the study area is higher in the upper home fields and reduces as it moves into the distant poor grazing lands (Figure 3-7). The NDVI varies spatially with the land use classes. The NDVI is higher in the forested areas, followed by crop fields and good grazing lands. The poor-grazing lands class has the lowest NDVI values. NDVI reflects not just level of land greenness, but also characterizes the amount of healthy aboveground vegetation biomass. Forested areas are expected to have higher NDVI due to the tree cover. Similarly, better NDVI is anticipated in the areas with crop fields and good grazing lands due to the cover of crops and natural grasses. However, low NDVI in poor grazing lands correctly revealed low cover of vegetation. Poor grazing lands are characterized by stoniness, bareland and low cover of grass biomass. Consistent with this work, the values of NDVI is been used as a forage scarcity index in Marsabit County and other similar parts of Kenya (Vrieling, Meroni et al. 2015). Also, the use of NDVI as a predictor for crop yields has been reported (Lewis, Rowland et al. 1998).

3.5 Conclusion

Crop fields and grazing lands are important land use classes for provision of human food and livestock feed. Crop fields and good grazing lands in Marsabit-central, are located in high altitude areas, while poor grazing lands cover the lower altitude areas. Additionally, this work showed that NDVI varies with different land use classes and and also varies with the altitude. NDVI can be used as a proxy measure of aboveground forage biomass and crop yield.

Chapter 4 : Rainfall pattern and production of forage biomass

4.1 Introduction

Rainfall is important for the livelihoods of humans and in supporting ecosystem services. Rain-fed agriculture is the dominant food production system in SSA. Rain-fed farming in SSA is estimated to be 97% of the total crop land (Calzadilla, Zhu et al. 2013). The pattern of rainfall affects the steadiness in production of food and forage biomass. The necessity of rainfall is more pronounced in arid and semi-arid areas where people and livestock populations are exclusively dependent on erratic rainfall for production of human food and livestock feed.

In Marsabit, and also most parts of East Africa, there are two rain seasons per year. The long rain season is a period from March/April to July/August, while the short rain season is from October/November to December (Ngetich, Mucheru-Muna et al. 2014). It is during the long rain season that most farmers across East Africa, grow their food crops and it is the important season for the production of natural forages. The long rain season is therefore important in sustaining food security.

The information on the long rain season in Marsabit is constrained by the remoteness of its location as well as vastness of the county. Additionally, the number of gauged stations for collecting rainfall data is limited. The knowledge on rainfall is further blurred by high spatial and temporal variability. Yet, the dynamics of rainfall in Marsabit controls the performance of crop and livestock-based livelihoods.

The livestock production system in Marsabit depends on natural forage biomass. The quantity of forage biomass produced per rain season determines the availability of livestock feed. In Marsabit-central, natural forage biomass produced in upper individual grass fields and the forage biomass in low-lying common grazing lands regulate the sustainability of livestock production.

> This chapter addresses objective 2: *To understand the spatial and temporal variability of rainfall and its influence on production of forage biomass*

The chapter seeks to:

i. Show the mean, median, quartiles and interquartile ranges of historical rainfall at Marsabit town.
ii. Identify the probability of exceedance for annual and seasonal rainfall.
iii. Reveal the real-time rainfall information of 2016 and 2017 long rain seasons.
iv. Report on the spatial rainfall pattern in wet, median and dry seasons.
v. Describe the forage production in upper home fields and lower grazing lands under different rainfall conditions.

4.2 Methods of study

4.2.1 Acquiring historical rainfall data

The historical rainfall data sourced was for Marsabit town. The data from the year 1960 to 2013 was acquired from the meteorological service in Nairobi, Kenya. The rainfall data collected by meteorological service within the long seasons of 2016 and 2017 was received from the government service in Marsabit. The acquired rainfall data was on monthly basis.

The historical rainfall data was used to calculate the trend of rainfall.

Trend of the historical rainfall

The trend of the rainfall involved the variability of annual total rainfall over the years.

The mean of the historical rainfall was calculated as follows:

$$\text{Mean rainfall (mm)} = \frac{\text{Total rainfall for all the years (mm)}}{\text{Number of years}}$$

Measures of dispersion for historical rainfall was computed. First quartile (Q1) and the third quartile (Q3) were calculated and the interquartile range determined.

$$\text{Interquartile range of rainfall (mm)} = \text{Q3} - \text{Q1}$$

A line graph showing the mean, median, first quartile and third quartile is then displayed. The graphical result depicts the trend of rainfall in Marsabit town.

Probability of Exceedance (PoE)

Probability of exceedance was also calculated using the historical rainfall data. Probability of exceedance is a percent chance that certain amount of rainfall (mm) occurs in any given time (year or season) (https://water.usgs.gov/edu/100yearflood.html, accessed 19th Jan. 2018).

The procedure for calculating probability of exceedance involved the following:

1. Ranking the historical rainfall data. With the highest annual or seasonal rainfall ranked as number 1.

2. Probability of Exceedance (PoE) was then calculated as follows:

$$PoE = \frac{m}{n+1}$$

Where *m* is the event rank, and *n* is the data points (total number of years or seasons for which rainfall data are acquired).

4.2.2 Measuring rainfall of 2016 and 2017 long seasons

Standard rain gauges were bought from Metcheck Weather Instrumentation Company in UK (Figure 4-1). The rain gauges were used to collect real-time rainfall data in the study area. They were used to record rainfall during the long rain seasons of 2016 and 2017. Nine rain gauges were used. Six rain gauges were placed in different upper individual crop farms and 3 placed in various sites within the lower grazing lands (Table 4-1). The rain gauges were positioned on the ground, 15 m away from any trees and buildings. To each rain gauge, a literate person was deployed to take care of rain gauge as well as taking the readings at 8.00am of every morning. The rainfall readings were taken throughout the long rain season of each year.

Type: ClimeMet CM1037 traditional copper raingauge. Manufacturer: Metcheck Weather Instrumentation, UK.

Figure 4-1: Standard rain gauge

Table 4-1: Geographical positions of rain gauges and Gov't Met service

Location	Sites/Farms	Latitude (dd)	Longitude (dd)	Altitude (m)
DK	DKMB	2.330	38.022	1281
DK	DKJG	2.320	38.023	1268
DK	DKED	2.342	38.032	1251
SG	SGLK	2.246	37.984	1002
SG	SGJM	2.248	37.997	1015
SG	SGJD	2.238	37.997	1007
GL	GLSK	2.390	38.061	1143
GL	GLKB	2.366	38.125	738
GL	GLKQ	2.329	38.183	642
Marsabit town	Gov't Met[1]	2.339	37.971	1353

[1]Gov't Met means government meteorological department. The department that measures, collate, and provides rainfall and other climate related data.

4.2.3 Measuring the production of forage biomass

There is a KALRO-Marsabit research centre in the area of study. Some of the KALRO facilities and equipment were used for conducting the study. A KALRO GPS machine with ±3 m error was used to record the geographical positions of the study plots. Other materials used were tape measure for measuring size of the quadrats and sisal ropes for fencing the quadrats. Sickle was also used to harvest the aboveground forage biomass and the field weighing balance for measuring the fresh weight of the biomass. Oven was used to dry the samples of the biomass in order to determine the weight of dry matter.

The production of forage biomass was studied in the months of May and August of 2016 and in the month of July 2017. The study was carried out on high altitude areas and also within the lower area of grazing lands.

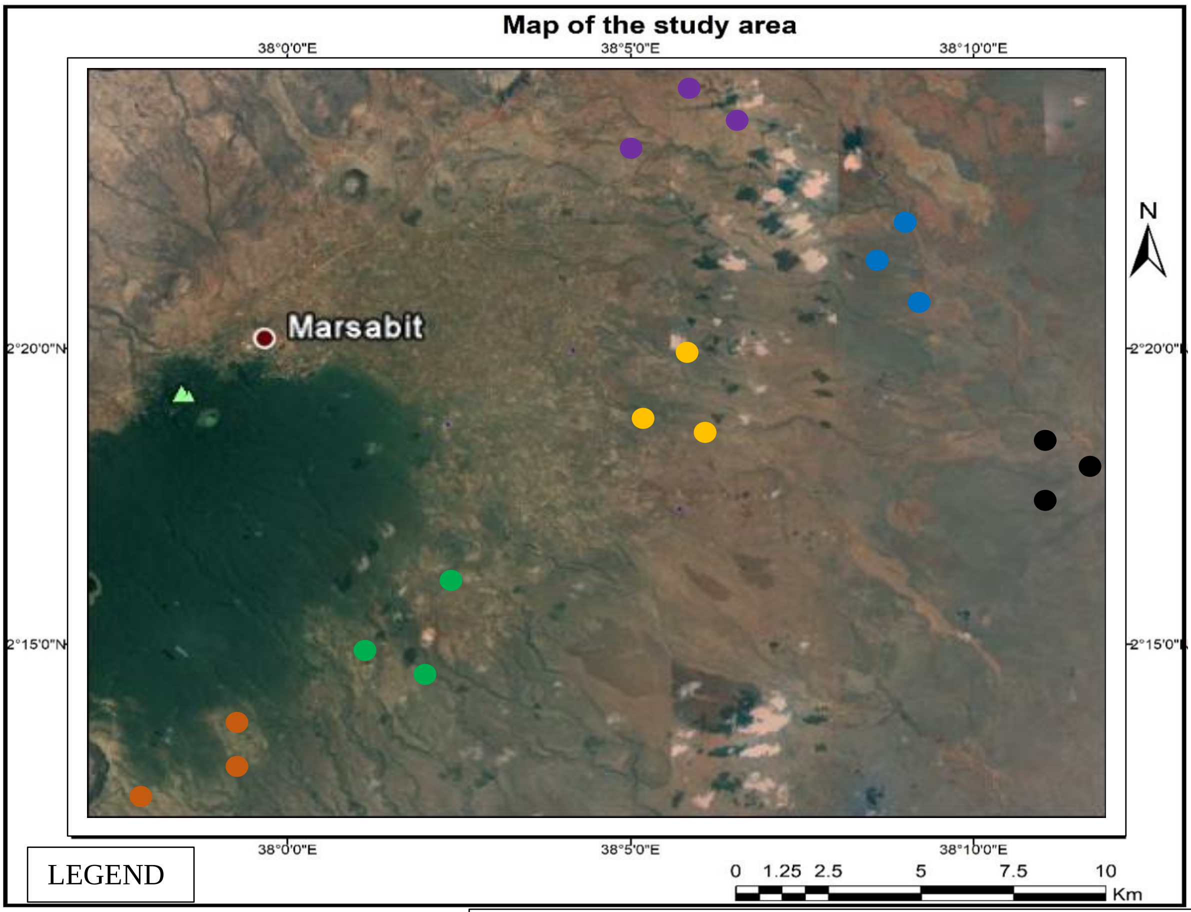
Production of forage biomass in the lower grazing lands (lowlands)

In the lower grazing lands (GL), 3 sites were selected. These were GLSK, GLKB and GLKQ sites. Site GLSK is in the class of good grazing lands, while sites GLKB and GLKQ belongs to the class of poor grazing lands (Figure 3-2). In each site, three 60 m x 60 m plots were randomly sampled. This involves researcher standing in a central point of a site. The directions including N, NE, E, SE, S, SW, W and NW were written on small different papers. The papers were mixed thoroughly and a single paper representing direction of bigger 60 m x 60 m plot is randomly selected. The researcher walks 200 m in the direction identified and lay the bigger 60 m x 60 m plot. Having located the sample position, its geographical coordinates were then recorded with the use of GPS. This is done 3 times in one site to select the three 60 m x 60 m plots. Each of the 60 m x 60 m plot is then divided into quadrats of 3 m x 3 m (9 m^2). These resulted in 400 different quadrats, each having an area of 9 m^2. Each quadrat within the bigger 60 m x 60 m plot is given a unique code. All the unique codes representing different quadrats were written on small different papers. The papers with unique codes were folded and placed in a single bucket, and thoroughly mixed. Then from the bigger one 60 m x 60 m plot, seven papers each representing a 3 m x 3 m (9 m^2) quadrat were randomly sampled. In 9 m^2 quadrat, all the aboveground forage biomass was harvested and fresh weight measured. The sample of forage biomass was placed in an oven at 105 ^oC for 24 hours and dry weight determined. The same procedure was done in GLSK, GLKB and GLKQ sites of lower grazing lands (Figure 4-2).

Production of forage biomass in the home-based grass fields (Upper high altitude fields)

The crop farmers in high altitude areas (home-based fields), set aside some individual fields for natural forages. The forages are mainly used to feed the cattle during dry or drought season. The forages are also used by home-based livestock that provides milk and draft power.

In the home-based upper grass fields, sites SG, BD and SA were selected (Figure 4-2). These sites are in the class of good grazing lands. In each site, 3 farms were sampled. In each farm, 3 plots each measuring 60 m x 60 m were randomly sampled. The sampling of bigger 60 m x 60 m plots and seven 3 m x 3 m (9 m^2) quadrats in the plot followed same procedure as in the lower grazing lands. Then from each quadrat of 9 m^2, all aboveground forage biomass was harvested and fresh weight taken while in the fields. The sample of forage biomass was placed in an oven at 105 ^oC for 24 hours and dry weight determined.



- SG grazing land
- BD grazing land
- SA grazing land
- GLSK grazing land
- GLKB grazing land
- GLKQ grazing land

Figure 4-2: Sites sampled for measuring forage biomass

4.2.4 Determining Rain Use Efficiency (RUE) in the grazing lands

RUE is the ratio of aboveground net primary productivity (kg/ha) to the rainfall precipitation (mm) (Fensholt and Rasmussen 2011). For the purpose of this study, water use efficiency is one and the same with RUE.

Rain Use Efficiency (RUE): RUE was determined from the DM forage biomass and rain.

It was calculated as follows:

$$\text{RUE (kg/ha/mm)} = \frac{\text{DM Forage biomass (kg/ha)}}{\text{Rainfall (mm)}}$$

4.2.5 Modelling of the rainfall

Summarized general steps in building the rainfall model

1. Rainfall was measured in 9 different sites during 2016 and 2017 long rain seasons
2. The rainfall data collected by the government service in same seasons of study and previous seasons was acquired
3. Ratio of site rainfall to government-collected rainfall was determined
4. The ratio was used to calculate rainfall of previous seasons for each site of study
5. Calculating the quantity of rainfall in the study sites during past long seasons
6. Acquiring the Digital Elevation Model (DEM) of the study area
7. Regression analysis between the rainfall and DEM was run
8. Linear regression model for spatial modelling of rainfall was defined for every season

4.2.5.1 Equations for calculating the rainfall of the study sites

The ratios of the rainfall data collected from the study sites in the season of 2016 to the government meteorological rainfall in same season were calculated. The reference rainfall of Marsabit government meteorological station is highlighted. The ratio was used to calculate historical rainfall for each site (Table 4-2).

Table 4-2: Ratios used for calculating seasonal rainfall of the study sites

Sites	Seasonal Rainfall (2016) (mm)	Ratio = (Site rainfall / Gov't Met rainfall)	Equations used for calculating seasonal rainfall for each site
Gov't Met	598.2	598.2/598.2=1.000	1 * Gov’t Met long season rainfall (mm)
DKED	565.6	565.6/598.2=0.946	0.946 * Gov’t Met long season rainfall (mm)
DKJG	572.0	572.0/598.2=0.956	0.956 * Gov’t Met long season rainfall (mm)
DKMB	541.2	541.2/598.2=0.905	0.905 * Gov’t Met long season rainfall (mm)
GLKB	359.9	359.9/598.2=0.602	0.602 * Gov’t Met long season rainfall (mm)
GLKQ	364.9	364.9/598.2=0.610	0.610 * Gov’t Met long season rainfall (mm)
GLSK	410.9	410.9/598.2=0.687	0.687 * Gov’t Met long season rainfall (mm)
SGJM	501.9	501.9/598.2=0.839	0.839 * Gov’t Met long season rainfall (mm)
SGJD	488.0	488.0/598.2=0.816	0.816 * Gov’t Met long season rainfall (mm)
SGLK	446.4	446.4/598.2=0.746	0.746 * Gov’t Met long season rainfall (mm)

4.2.5.2 Spatial modelling of long rain seasons

The predictor used for spatial modelling of rainfall was Digital Elevation Model (DEM). The original predictor was in the form of raster tiff image. The raster tiff image was converted into raster grd and raster gri. file. This was to make it possible for the R raster package to clearly read the raster data.

Linear regression was run to identify the relationships between the rainfall values and the Digital Elevation Model (DEM). Regression equations to model the spatial rainfall were determined from the coefficients of these linear regression results.

Using the identified regression model, the predicted pattern of rainfall across the study sites could be calculated in R software with the use of raster package.

4.2.5.3 Spatial modelling of forage biomass

The Rain Use Efficiency (RUE) of forages from this study and from other studies (Prince, De Colstoun et al. 1998, Paruelo, Lauenroth et al. 1999, Bai, Wu et al. 2008, Ruppert, Holm et al. 2012) in a similar environment, were averaged. This resulted in RUE of 8.7 kg/ha/mm (Table 4-3). This RUE was then used to model the biomass produced by the study sites. DM forage biomass was calculated across the study sites by multiplying raster files of spatial rainfall by RUE (kg/ha/mm).

Table 4-3: RUE used to model spatial forage biomass

RUE (kg/ha/mm)	Sources
7.7	(Paruelo, Lauenroth et al. 1999)
8.9	(Prince, De Colstoun et al. 1998)
7.8	(Bai, Wu et al. 2008)
8.2	(Ruppert, Holm et al. 2012)
7.9	Own work
10.0	Own work
9.8	Own work
8.9	Own work
8.7	Mean

4.2.5.4 Linear regression model for spatial analysis of 2016 and 2017 seasons

The following model was used to perform spatial analysis of 2016 long rain season:

Rainfall 2016 long rain season (mm) =0.325 * DEM + 137.328

R^2=0.79

The DM forage biomass for the 2016 long rain season was calculated as follows:

2016 long rain season DM forage biomass (kg/ha) = the raster file of 2016 long season rainfall (mm) * 8.7 (kg/ha/mm).

The 2017 long rain season was modelled using the following equation:

Rainfall 2017 long rain season (mm) =0.035 * DEM + 148.031

R^2=0.01

The DM forage biomass for the 2017 long rain season was calculated as follows:

2017 long rain season DM forage biomass (kg/ha) = the raster file of 2017 long season rainfall (mm) * 8.7 (kg/ha/mm).

4.2.5.5 Spatial modelling of rainfall and forage biomass under different conditions

In addition to the long rain seasons of 2016 and 2017, rainfall and forage biomass were modelled for the following five conditions of long season rainfall. These include: wet season (with 10% PoE), season with 25% PoE, season with 50% PoE (median season), season with 75% PoE, and the dry season (with 90% PoE).

Rainfall with 10% Probability of Exceedance (Wet season)

The following linear regression model was used to calculate rainfall of wet season:

Rainfall with 10% probability of exceedance (mm) =0.343 * DEM + 144.870

R^2=0.79

DM forage biomass produced in the season (kg/ha) = Raster file of rainfall with 10% probability of exceedance (mm) * 8.7 (kg/ha/mm)

Rainfall with 25% Probability of Exceedance (PoE)

The following linear regression model was used to calculate rainfall with 25% PoE:

Rainfall with 25% probability of exceedance (mm) =0.242 * DEM + 102.180

R^2=0.79

DM forage biomass produced in the season (kg/ha) = Raster file of rainfall with 25% probability of exceedance (mm) * 8.7 (kg/ha/mm)

Rainfall with 50% Probability of Exceedance (PoE)

The following linear regression model was used to calculate rainfall with 50% PoE:

Rainfall with 50% probability of exceedance (mm) =0.190 * DEM + 80.363

R^2=0.79

DM forage biomass produced in the season (kg/ha) = Raster file of rainfall with 50% probability of exceedance (mm) * 8.7 (kg/ha/mm)

Rainfall with 75% Probability of Exceedance (PoE)

The following linear regression model was used to calculate rainfall with 75% PoE:

Rainfall with 75% probability of exceedance (mm) =0.121 * DEM + 50.883

R^2=0.79

DM forage biomass produced in the season (kg/ha) = Raster file of rainfall with 75% probability of exceedance (mm) * 8.7 (kg/ha/mm)

Rainfall with 90% probability of exceedance (Dry season)

The following linear regression model was used to calculate rainfall of dry season:

Rainfall with 90% probability of exceedance (mm) =0.084 * DEM +35.306

R^2=0.79

DM forage biomass produced in the season (kg/ha) = Raster file of rainfall with 90% probability of exceedance (mm) * 8.7 (kg/ha/mm)

4.2.6 Calculation of forage biomass from upper home fields to lower grazing lands

Forage biomass against the distance was studied. This involved distance from the upper home fields to the lower grazing lands. It was determined for the following seasons: a) Forage produced in 2016 long season, b) Forage produced in 2017 long season, c) Forage produced during wet season (with 10% PoE), d) Forage produced during season with 25% PoE, e) Forage produced during median season (50% PoE), f) Forage produced during season with 75% PoE, g) Forage produced during dry season (with 90% PoE).

The forage biomass was calculated along the transect. Transect measuring 22 km long was selected for each of the season. For each of the season, the transect started from 38.00 easting, 2.30 northing, and ended at 38.20 easting, 2.30 northing. The production of forage biomass along the transect was computed.

The unit of transect (distance) was in degree decimal. One degree decimal is approximately 111 km in south and north of equator (Gohari, Ahmad et al. 2012, Croicu and Kreutz 2017). Therefore, the distance in degree decimal was multiplied by 111 to convert the distance into km. The forage biomass (kg/ha) against the distance (km) was displayed.

This is followed by calculation of forage biomass within a radius of 22 km, with the centre at 38.00 Easting and 2.30 Northing. The DM forage biomass in a half circular area was computed. The cumulative DM forage biomass was calculated and the results presented against the distance.

Statistical analysis

R statistical software was used for analysis. Means, standard errors and standard deviations were computed. The parameters were also subjected to none linear model of analysis of variance (ANOVA) at the 95% (P<0.05) level of confidence. Location was used as a random factor. When ANOVA results show significant differences, Tukey's HSD test was used to analyse the differences between different sites.

4.3 Results

4.3.1 Rainfall dynamics in Marsabit-central

4.3.1.1 Trend of rainfall events in Marsabit-central

The annual total rainfall recorded at Marsabit town in the last 50 years has been highly variable with annual mean 727.0 mm, median 687.0 mm, first quartile 506.6 mm, third quartile 880.4 mm, and interquartile range of 373.8 mm (Figure 4-3). The variability of rainfall affects the production of forage biomass.

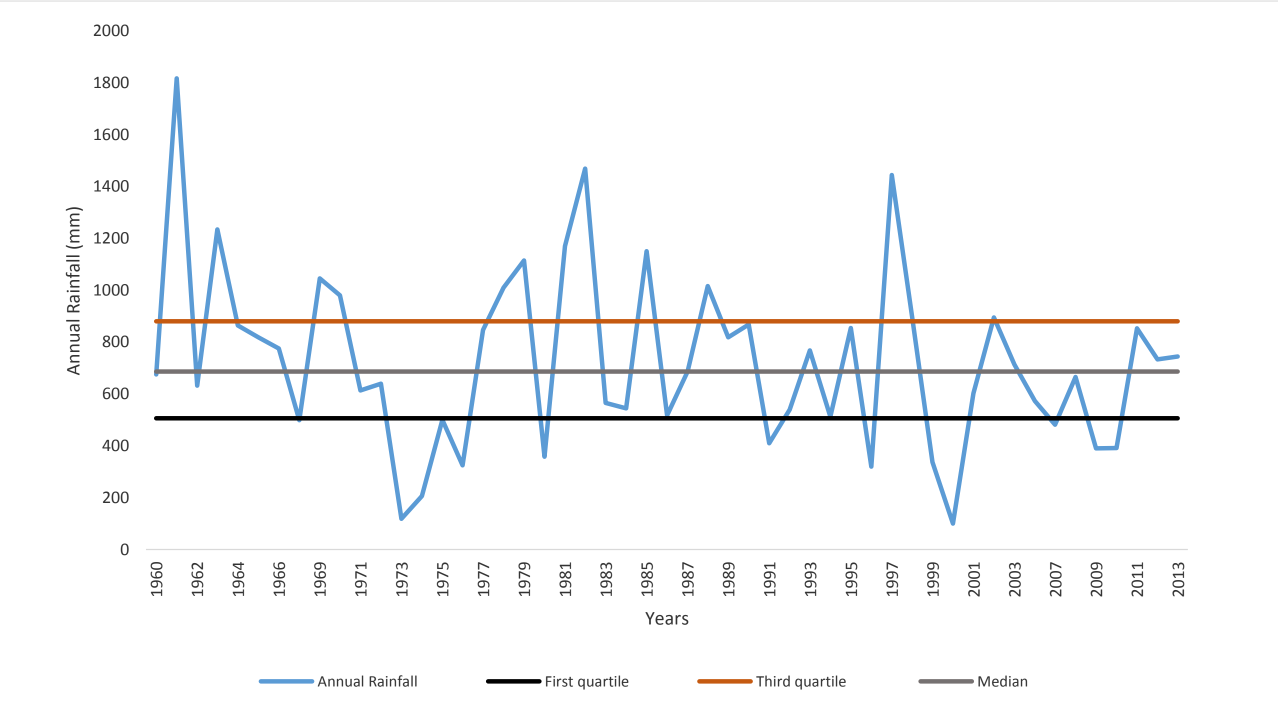


Figure 4-3: Annual Rainfall (mm) in Marsabit-central, Kenya

4.3.1.2 Probability of exceedance for rainfall in Marsabit-central

The probability of exceedance was calculated using rainfall data from 1960 to 2013. The probability that any annual rainfall can be equal to 600.0 mm is 58% (Figure 4-4).

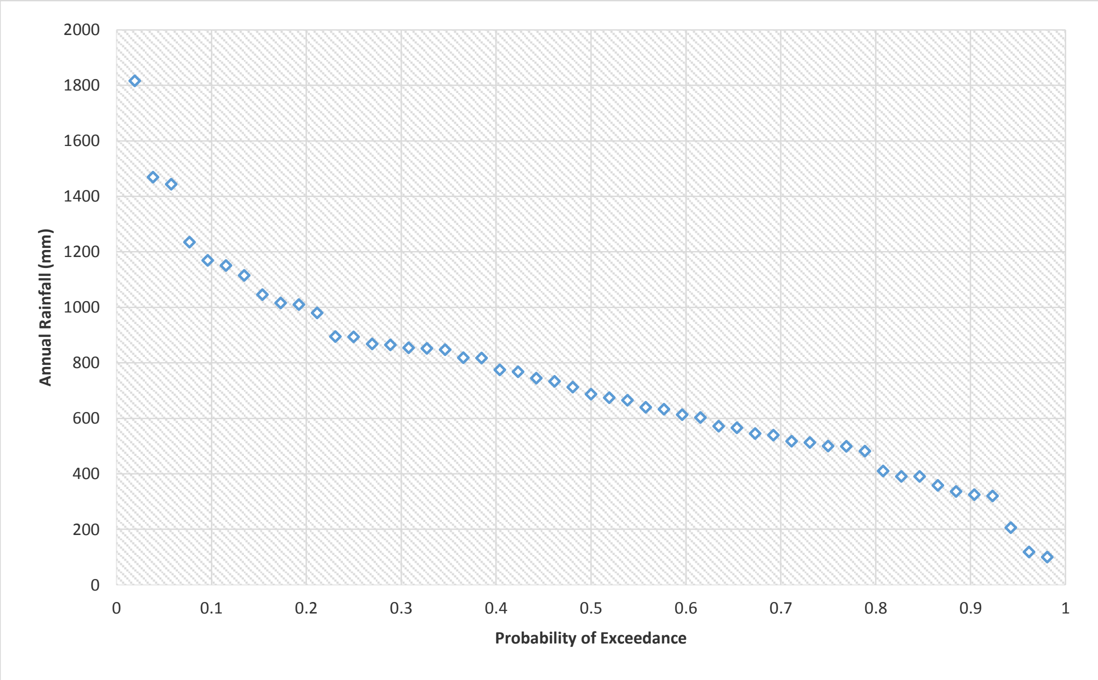


Figure 4-4: PoE for annual rainfall (Marsabit town)

There is 55% chance for the study area to receive 300.0 mm of rainfall for any long rain season (Figure 4-5).

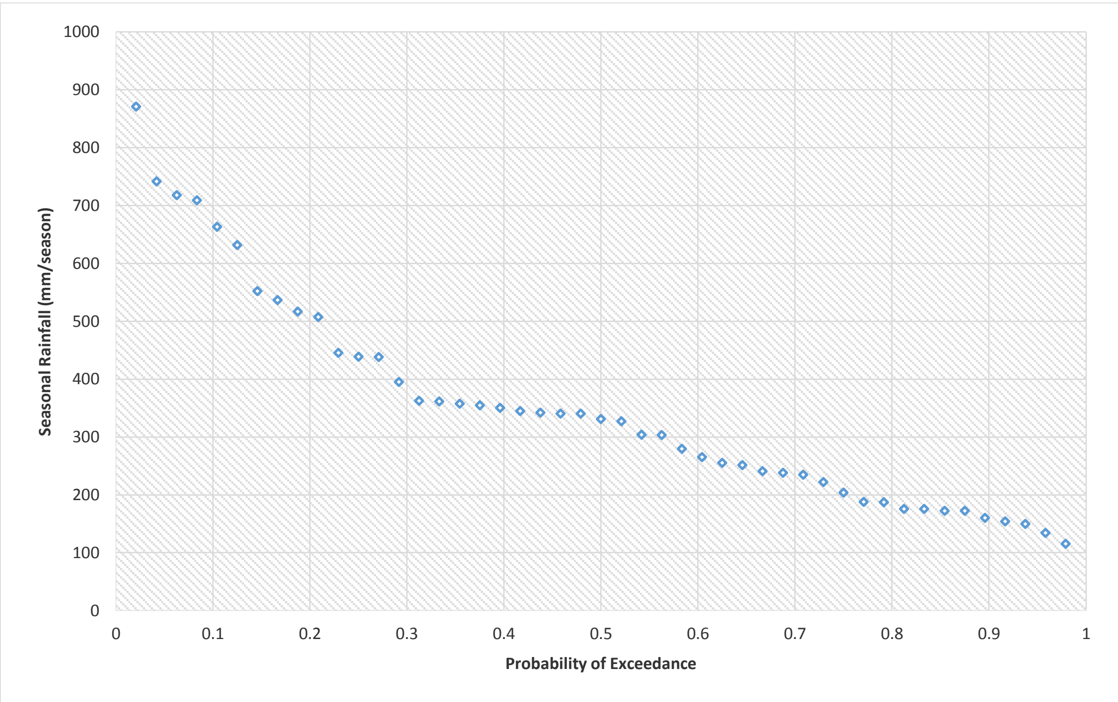


Figure 4-5: PoE for long rain season (Marsabit town)

4.3.1.3 Temporal variability of rainfall in Marsabit-central

The amount of rainfall in the season of 2016, was higher than the rainfall in the season of 2017, in all the study sites and also at the government meteorological service. The differences in quantity of rainfall received in the long seasons of 2016 and 2017 exhibits temporal inconsistency of rainfall in the study area (Table 4-4).

Table 4-4: Long rain season; April – August rainfall in different sites

Locations	Sites	Altitude (m)	Total Rainfall (mm) 2016	Total Rainfall (mm) 2017
BD	BDRB	1010		267.3
DK	DKED	1251	565.6	155.3
DK	DKJG	1268	572.0	149.6
DK	DKMB	1281	541.2	158.8
GL	GLKB	738	359.9	95.5
GL	GLKQ	642	364.9	69.9
GL	GLSK	1143	410.9	83.0
SG	SGJM	1015	501.9	378.0
SG	SGJD	1007	488.0	299.2
SG	SGLK	1002	446.4	312.3
Gov't Met service[b]	Meteorological station	1353	598.2	151.7

[b]This is a government meteorological station.

4.3.1.4 Spatial variability of rainfall in Marsabit-central

Marsabit is the second largest county in Kenya covering about 70,961 km^2 (GoK, 2013). The only established and staffed meteorological station covering this vast area is the service in Marsabit town. This study showed disparity between rainfall recorded by government meteorological service (Table 4-5), and the rainfall recorded in the sites of study (Table 4-4).

Table 4-5: Rainfall data recorded by government meteorological service in long rain seasons

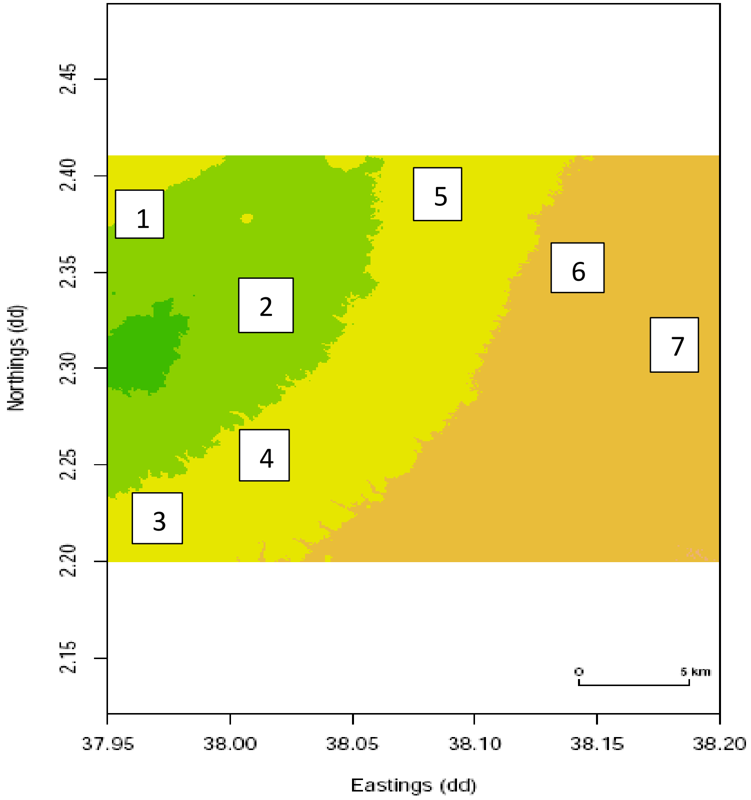
Month	2016 rainfall (mm)	2017 rainfall (mm)
April	526.7	76.2
May	61.5	55.8
June	9.0	0.0
July	1.0	6.4
August	0.0	13.3
Total	598.2	151.7

The amount of rainfall also differed significantly among the locations of the study ($P \leq 0.05$). Altitude ranges from 1281 - 928 metre above sea level (m asl) in the upper fields and dropping to around 600 m asl in the lower grazing lands. Altitude had significant impact on the spatial distribution of rainfall ($P \leq 0.05$), with high altitude areas having tendency of higher amount of rainfall than lower grazing areas (Table 4-6) (Figure 4-6).

Table 4-6: Long rain season; April – August rainfall in different locations

Land use classes	Locations	Rainfall (mm) – Means and SE 2016	Rainfall (mm) – Means and SE 2017	Altitude (m asl) – Means and SE
Crop fields	DK	559.6(9.4)a	154.6(2.7)b	1266.7(8.7)a
Crop fields	SG	478.8(16.7)b	329.8(24.4)a	1008.0(3.8)ab
Grazing lands	GL	378.6(16.2)c	82.8(7.4)c	831.0(149.8)b
Altitude effect *P* Value ($P \leq 0.05$)		<0.001	<0.001	

Means in each column that do not share a letter are significantly different at $P \leq 0.05$, by Tukey's HSD test. Values are given as mean at each location with SE in parentheses.



KEY

1: Rainfall data record of **government meteorological service**:
Altitude (m)= 1353
2016 season: 598.2mm
2017 season: 151.7mm

2: DK location: Average altitude (m) =1267

Rainfall in 2016	Rainfall in 2017
DKED farm: 565.5mm	DKED farm: 155.3mm
DKJG farm: 572.0mm	DKJG farm: 149.6mm
DKMB farm: 541.2mm	DKMB farm: 158.8mm

3: SG location: Average altitude (m)=1008

Rainfall in 2016	Rainfall in 2017
SGJD farm: 488.0mm	SGJD farm: 299.2mm
SGLK farm: 446.4mm	SGLK farm: 312.3mm
SGJL farm: 501.9mm	SGJL farm: 378.0mm

4: BD location: Altitude (m)=1003
Rainfall in 2017: BDRB farm: 267.3mm
5: SK grazing land: Altitude (m)= 1137
Rainfall in 2016: 410.9mm, Rainfall in 2017: 83.0mm
6: KB grazing land: Altitude (m)=788
Rainfall in 2016: 359.9mm, Rainfall in 2017: 95.5mm
7: KQ grazing land: Altitude (m)=651
Rainfall in 2016: 364.9mm, Rainfall in 2017: 69.9mm

Figure 4-6: Map showing spatial variability of rainfall

The background is the spatial rainfall map of 2016 long rain season elaborated in the following section of this chapter.

4.3.2 Biomass production in the grasslands of upper home fields and in the lower grazing lands

The biomass production differed among the sites ($P \leq 0.05$). The grass biomass are used by cattle, which is the dominant livestock species in the study area. The shrubs are also non-grass forage plants used by livestock. The lowland grazing areas produce forage shrubs in addition to grass, and shrubs are not as palatable to livestock as grass. Also, GLKB and GLKQ sites are in the class of poor grazing lands while other sites are in the land use class of good grazing lands (Table 4-7).

Table 4-7**:** Production of forage biomass

Seasons	Sites	DM forages t/ha Means and SD	Land forms	Plant forms
2017	BD 1	4.77(1.09)	Upper fields	Grass
2017	BD 2	6.20(2.84)	Upper fields	Grass
2017	BD 3	6.49(1.05)	Upper fields	Grass
2017	SA 1	4.89(1.52)	Upper fields	Grass
2017	SA 2	7.86(1.64)	Upper fields	Grass
2017	SA 3	4.01(0.89)	Upper fields	Grass
2017	SG 1	5.24(1.70)	Upper fields	Grass
2017	SG 2	3.56(1.06)	Upper fields	Grass
2017	SG 3	4.75(0.82)	Upper fields	Grass
2016	GLKB 1	10.69(3.29)	Lowlands	Shrubs and grass
2016	GLKB 2	7.46(2.99)	Lowlands	Shrubs and grass
2016	GLKB 3	5.23(2.53)	Lowlands	Shrubs and grass
2016	GLKQ 1	8.16(3.24)	Lowlands	Shrubs and grass
2016	GLKQ 2	12.17(3.76)	Lowlands	Shrubs and grass
2016	GLKQ 3	7.30(1.19)	Lowlands	Shrubs and grass
2016	GLSK 1	6.08(0.60)	Lowlands	Grass
2016	GLSK 2	5.30(0.69)	Lowlands	Grass
2016	GLSK 3	6.73(2.87)	Lowlands	Grass

Values are given as mean at each site with SD in parentheses.

4.3.3 Spatial modelling of rainfall and forage biomass in 2016 and 2017 long seasons

4.3.3.1 Long rain season of the year 2016

There is spatial disparity of 2016 rain season, with an interquartile range of 138 mm (Table 4-8 and Figure 4-7).

Table 4-8: Summary of the 2016 long rain season

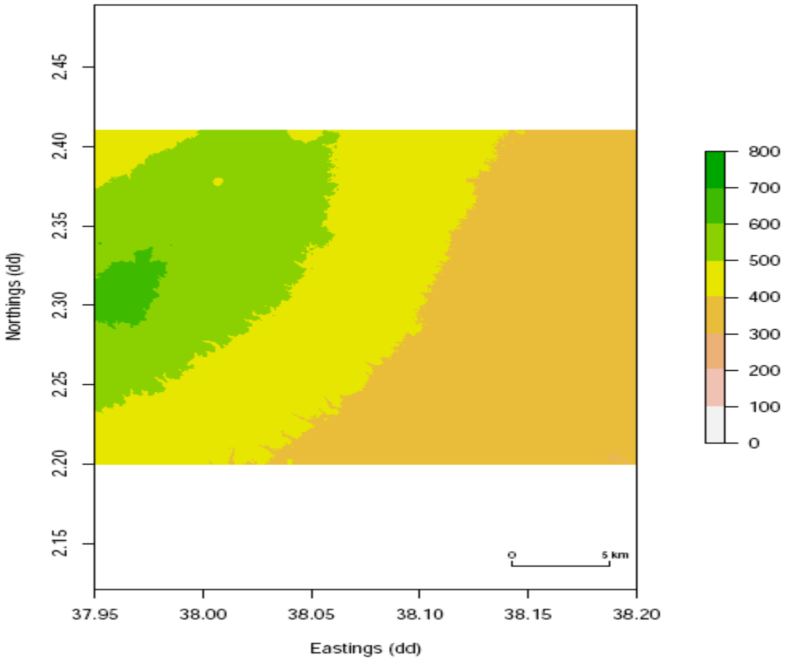
Statistics	Rainfall (mm)
Minimum	296.9
1st Quantile	364.7
Median	428.6
3rd Quantile	502.7
Maximum	687.5

DM forage biomass produced during the 2016 long rain season

The DM forage biomass of 2016 season ranges from 2583 - 5982 kg/ha, and has an interquartile range of 1200.9 kg/ha (Table 4-9 and Figure 4-8).

Table 4-9: Summary of DM forage biomass produced during the 2016 long rain season

Statistics	DM forage biomass (kg/ha)
Minimum	2583.1
1st Quantile	3172.8
Median	3729.5
3rd Quantile	4373.7
Maximum	5981.6



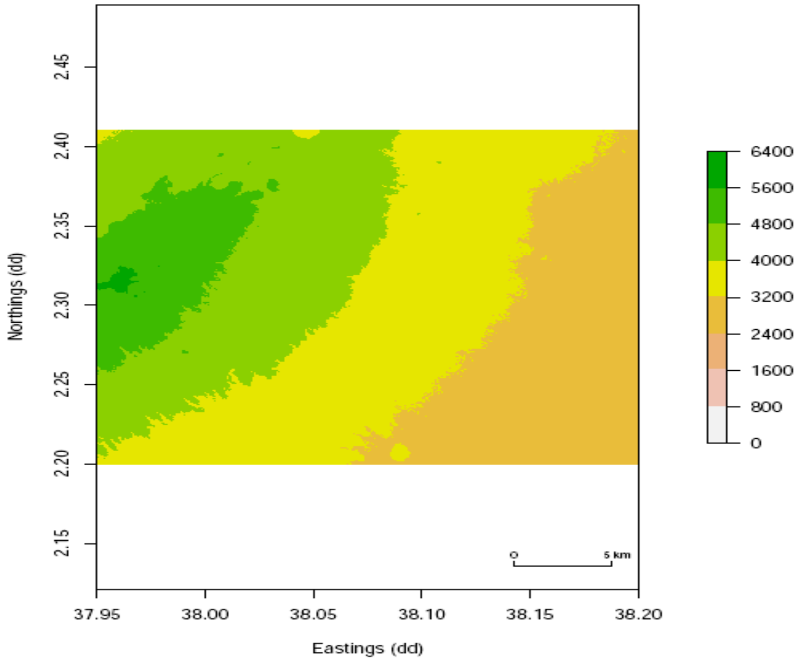


Figure 4-7: Rainfall during 2016 long rain season (mm)	Figure 4-8: DM forages produced during the 2016 long rain season (kg/ha)

4.3.3.2 Long rain season of the year 2017

The rainfall received in this season was below average. The season has an interquartile range of 14.8 mm (Table 4-10 and Figure 4-9).

Table 4-10: Summary of the 2017 long rain season

Statistics	Rainfall (mm)
Minimum	165.2
1st Quantile	172.5
Median	179.3
3rd Quantile	187.3
Maximum	207.2

DM forage biomass produced by 2017 long rain season

The DM forage biomass of 2017 season was lower than the one of 2016 season. The forage biomass produced in 2017 ranged from 1437-1804 kg/ha. It has an interquartile range of 129.1 kg/ha (Table 4-11 and Figure 4-10).

Table 4-11: Summary of DM forage biomass produced during 2017 long rain season

Statistics	DM forage biomass (kg/ha)
Minimum	1437.4
1st Quantile	1500.4
Median	1560.3
3rd Quantile	1629.5
Maximum	1803.7

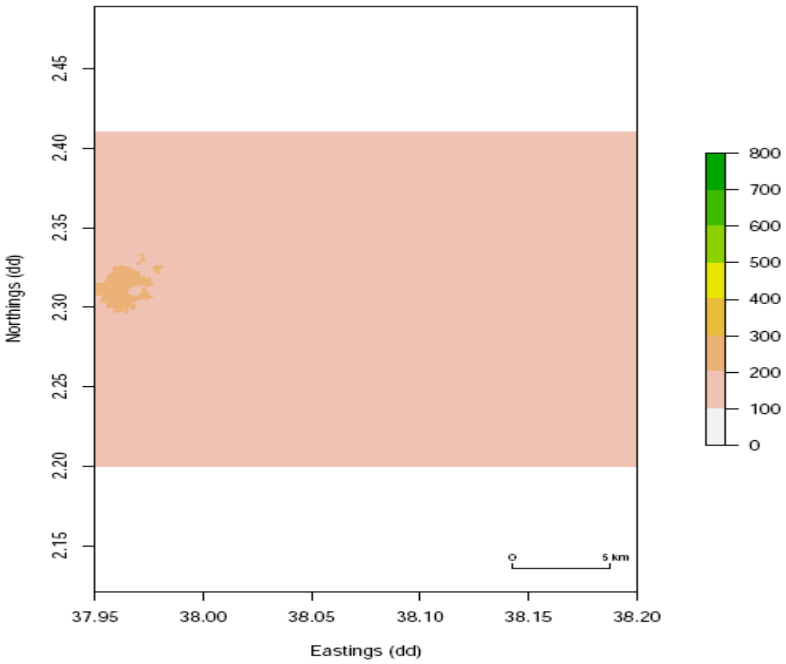
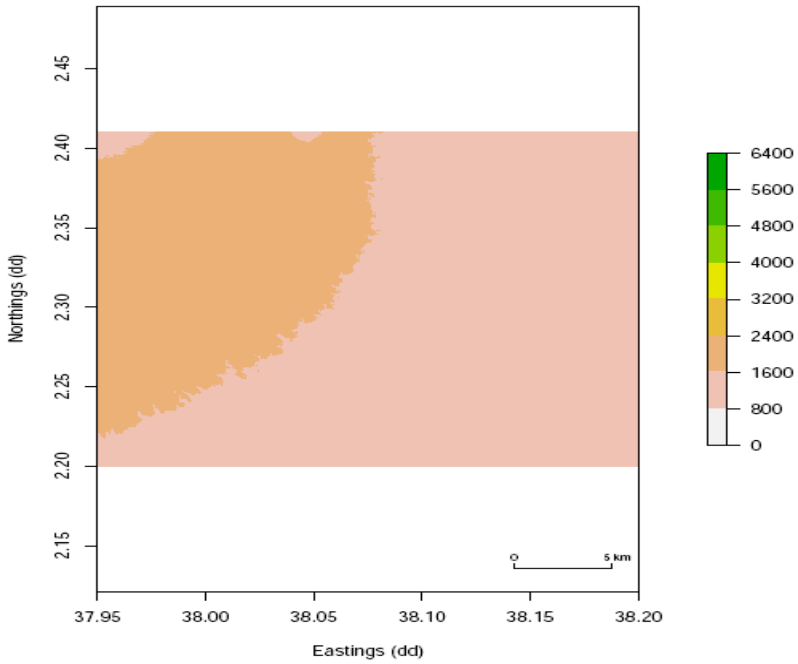
	

Figure 4-9: Rainfall during 2017 long rain season (mm)	Figure 4-10: DM forages produced during the 2017 long rain season (kg/ha)

4.3.4 Spatial modelling of long rain seasons and forage biomass under different conditions

Rainfall and forage biomass were modelled under the following conditions: Wet season (with 10% PoE), season with 25% PoE, median season (with 50% PoE), season with 75% PoE, and dry season (with 90% PoE). Altitude had significant influences on the spatial analysis of rainfall ($P \leq 0.05$). This is common across all the seasons of different rainfall conditions.

4.3.4.1 Rainfall during long wet season (10% PoE)

This is one of the wettest season that occurs in the study area. The rain season of 2016 also falls in this category of wet season. The wet long season has 10% probability of exceedance (Table 4-12 and Figure 4-11).

Table 4-12: Summary of rainfall during long wet season (10% PoE)

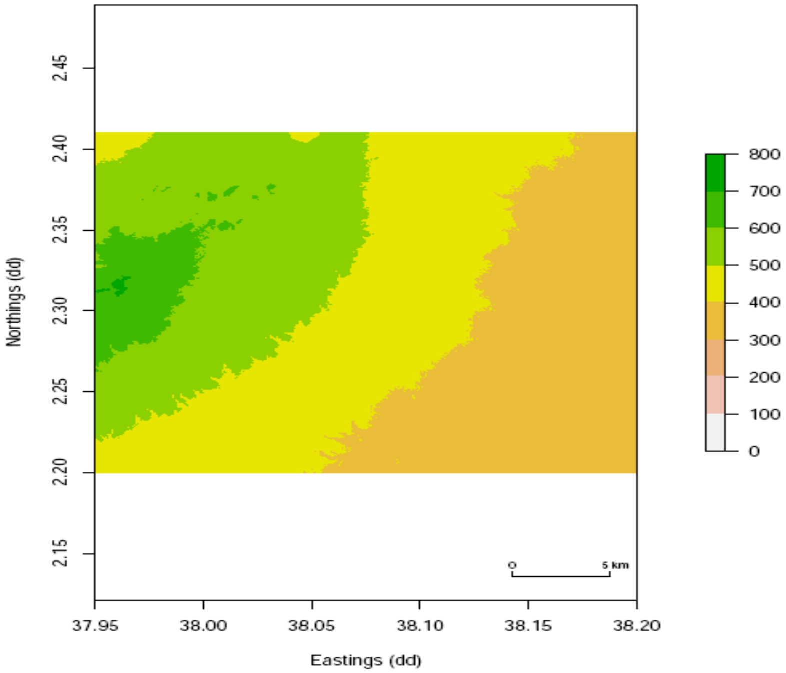
Statistics	Rainfall (mm)
Minimum	313.3
1st Quantile	385.0
Median	452.6
3rd Quantile	530.9
Maximum	726.1

Forage biomass produced during long wet season

This wet season translates to the season of highest forage production. The forage biomass produced in this season ranges from 2726 - 6317 kg/ha, and has an interquartile range of 1268.7 kg/ha (Table 4-13 and Figure 4-12).

Table 4-13: Summary of DM forage biomass produced during long wet season (10% PoE)

Statistics	DM forage biomass (kg/ha)
Minimum	2725.6
1st Quantile	3349.8
Median	3937.9
3rd Quantile	4618.5
Maximum	6316.9



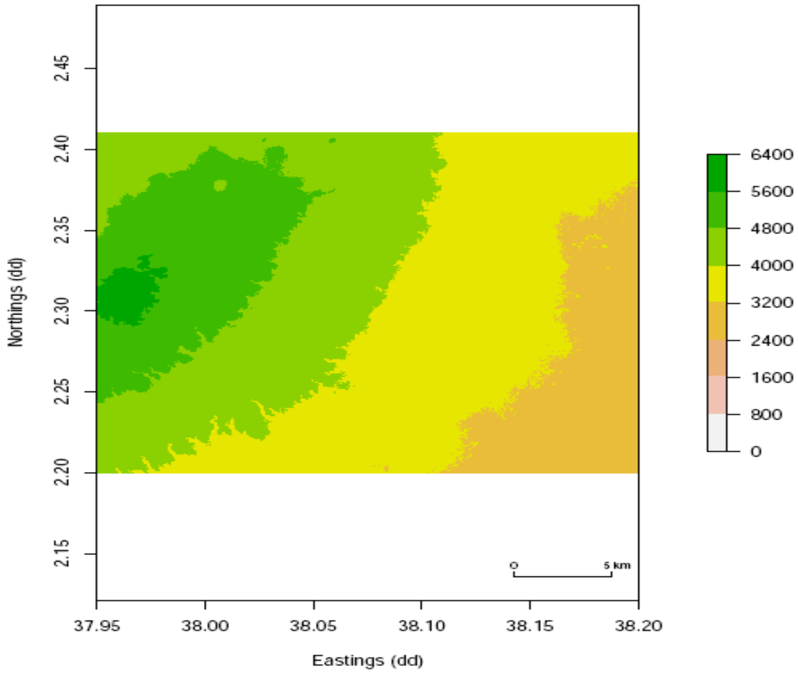


Figure 4-11: Rainfall during long wet season with 10% PoE (mm)	Figure 4-12: DM forages produced during long wet season with 10% PoE (kg/ha)

4.3.4.2 Long rain season with 25% probability of exceedance

The season with 25% probability of exceedance is a better season with good amount of rainfall. However, just like season with 10% PoE, this quantity of rainfall is not received uninterruptedly year after year (Table 4-14 and Figure 4-13).

Table 4-14: Summary of long rain season with 25% PoE

Statistics	Rainfall (mm)
Minimum	221.00
1st Quantile	271.6
Median	319.3
3rd Quantile	374.4
Maximum	512.2

Forage biomass produced during long season rainfall with 25% PoE

The season with 25% PoE produced forage biomass with an interquartile range of 894.8 kg/ha (Table 4-15 and Figure 4-14).

Table 4-15: DM forage biomass produced during long rain season with 25% PoE

Statistics	DM forage biomass (kg/ha)
Minimum	1922.7
1st Quantile	2362.7
Median	2777.5
3rd Quantile	3257.5
Maximum	4455.5

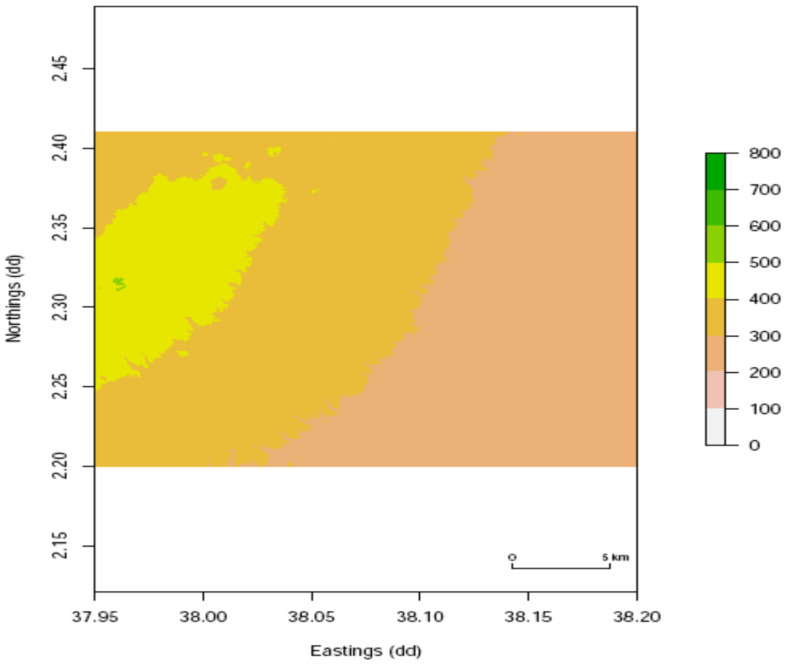


Figure 4-13: Rainfall during long rain season with 25% PoE (mm)

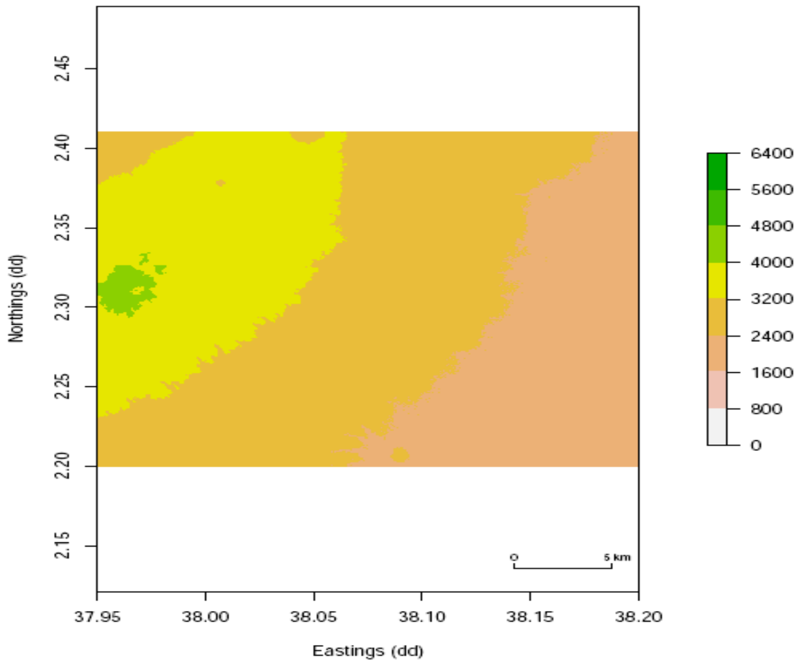


Figure 4-14: DM forages produced during long rain season with 25% PoE (kg/ha)

4.3.4.3 Long rain season with 50% probability of exceedance

This is a median season of rainfall. This pattern of rainfall is more frequently received than wetter seasons (Table 4-16 and Figure 4-15).

Table 4-16: Summary of long rain season with 50% PoE

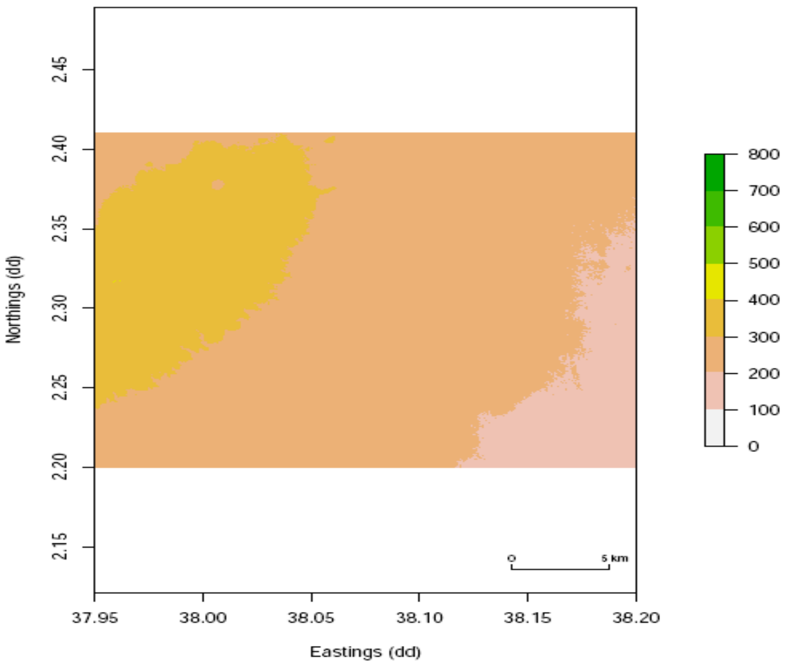
Statistics	Rainfall (mm)
Minimum	173.7
1st Quantile	213.6
Median	251.1
3rd Quantile	294.5
Maximum	402.7

Forage biomass produced during the long rain season with 50% PoE

The median season with 50% PoE produced dry forage biomass ranging from 1511 - 3504 kg/ha, and has an interquartile range of 703 kg/ha (Table 4-17 and Figure 4-16).

Table 4-17: DM forage biomass produced during long rain season with 50% PoE

Statistics	DM forage biomass (kg/ha)
Minimum	1510.8
1st Quantile	1856.3
Median	2181.9
3rd Quantile	2558.8
Maximum	3503.8



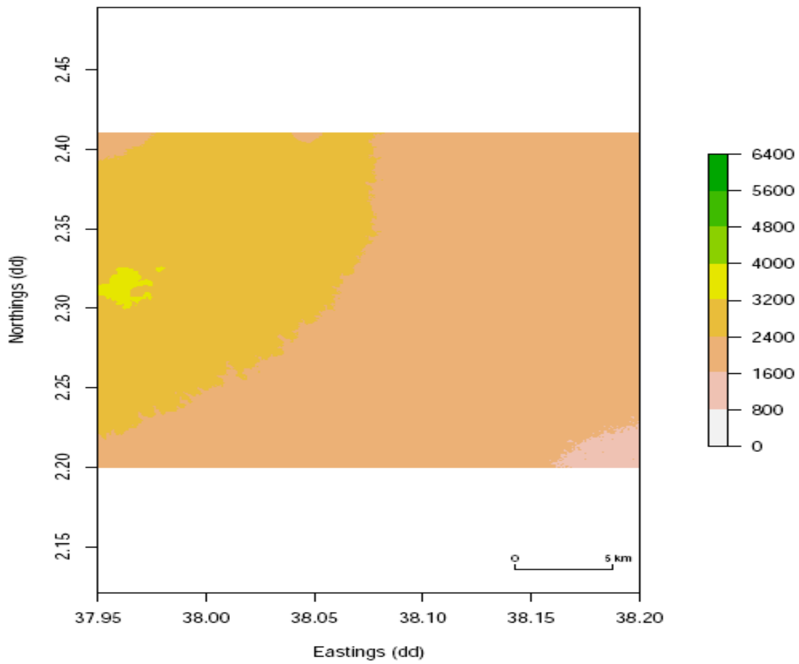


Figure 4-15: Rainfall during long rain season with 50% PoE (mm)	Figure 4-16: DM forages produced during long rain season with 50% PoE (kg/ha)

4.3.4.4 Long rain season with 75% probability of exceedance

This is a season of low rainfall, ranging from 110-256 mm (Table 4-18 and Figure 4-17).

Table 4-18: Summary of long rain season with 75% PoE

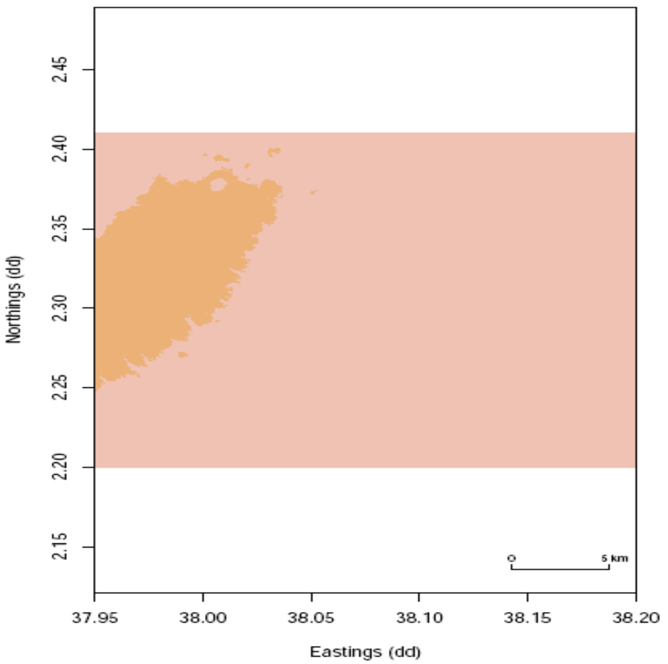
Statistics	Rainfall (mm)
Minimum	110.3
1st Quantile	135.6
Median	159.4
3rd Quantile	187.0
Maximum	255.9

Forage biomass produced during the long rain season with 75% PoE

This season with 75% PoE produced lower quantity of forage biomass (Table 4-19 and Figure 4-18).

Table 4-19: DM forage biomass produced during long rain season with 75% PoE

Statistics	DM forage biomass (kg/ha)
Minimum	959.6
1st Quantile	1179.6
Median	1387.0
3rd Quantile	1627.0
Maximum	2225.9



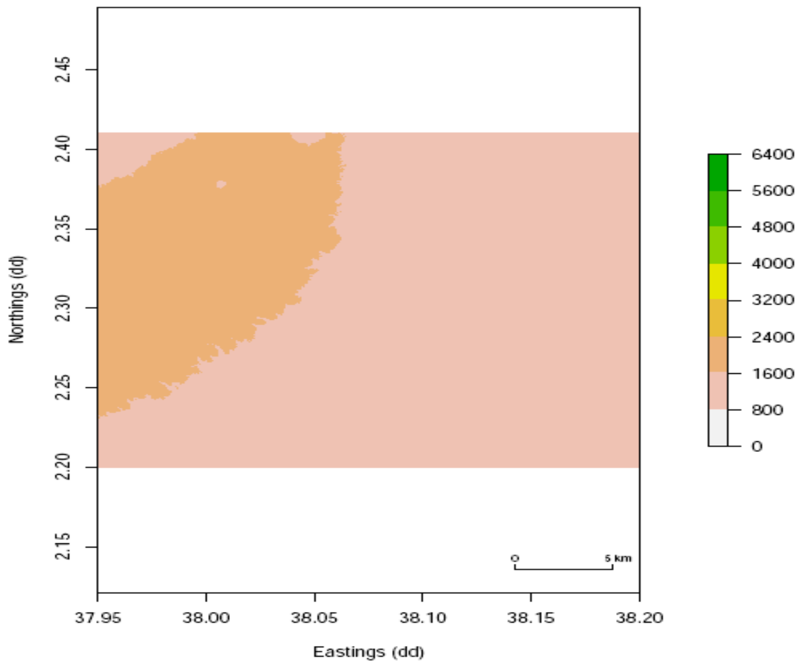


Figure 4-17: Rainfall during long rain season with 75% PoE (mm)	Figure 4-18: DM forages produced during long rain season with 75% PoE (kg/ha)

4.3.4.5 Rainfall during dry long season

This is one of the driest season that occurs in the study area. This dry season has 90% probability of exceedance. The long rain season of 2017 also falls in this category of dry season (Table 4-20 and Figure 4-19).

Table 4-20: Summary of rainfall during long dry season with 90% PoE

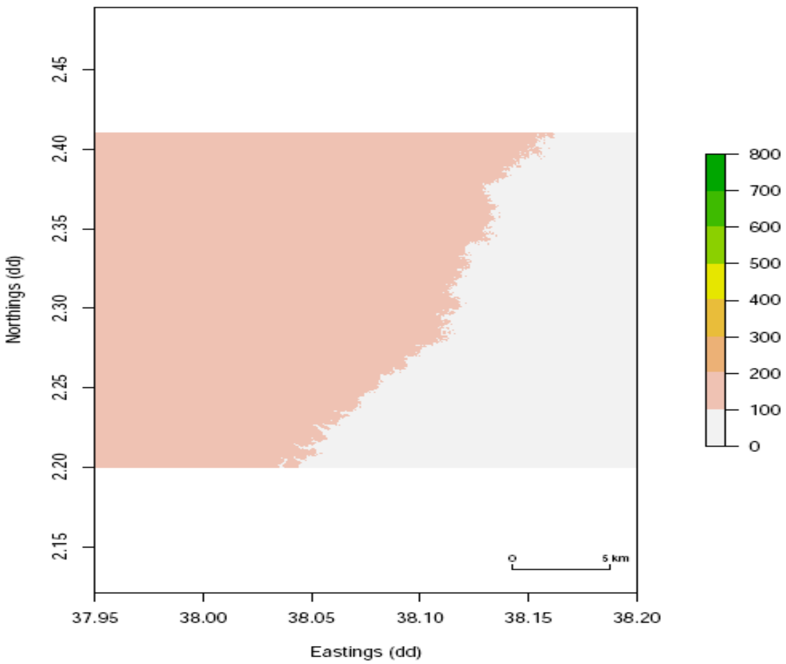
Statistics	Rainfall (mm)
Minimum	76.6
1st Quantile	94.1
Median	110.7
3rd Quantile	129.8
Maximum	177.6

Forage biomass produced during long dry rain season

Dry season produces lowest forage biomass across the study area, having an interquartile range of 310.6 kg/ha (Table 4-21 and Figure 4-20).

Table 4-21: DM forage biomass produced during long dry season with 90% PoE

Statistics	DM forage biomass (kg/ha)
Minimum	666.0
1st Quantile	818.7
Median	962.7
3rd Quantile	1129.3
Maximum	1545.1



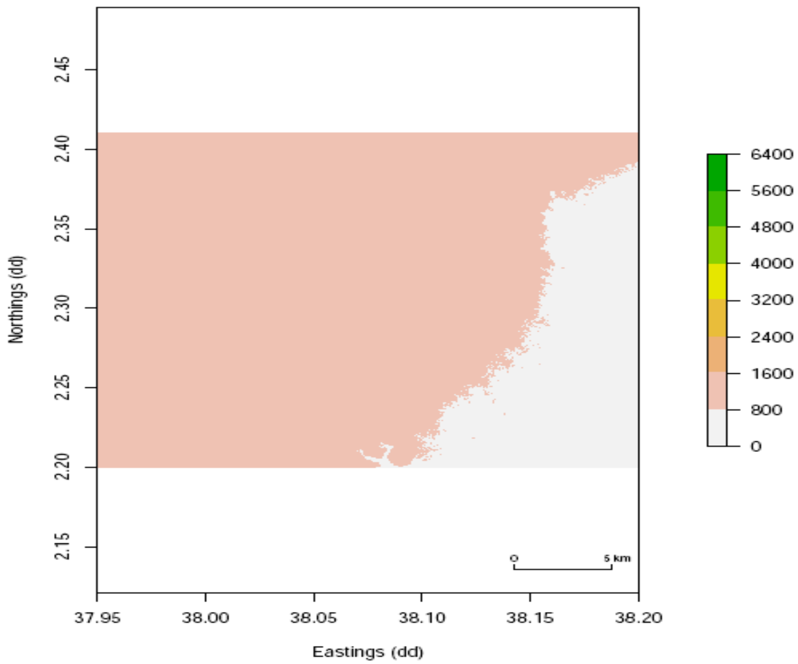


Figure 4-19: Rainfall during long dry season with 90% PoE (mm)	Figure 4-20: DM forages produced during long dry season with 90% PoE (kg/ha)

4.3.5 Variability of forage biomass from upper home fields to lower grazing lands

The upper home fields produce better quantity of forage biomass than the lower grazing lands. The upper fields are in the class of good grazing lands while the lower fields are in the class of poor grazing lands. During the dry season with 90% PoE, the forage production is generally low both in upper fields and lower fields. The dry season has low variability of forage production across the grazing lands.

Nevertheless, the production of forage biomass in wet and median seasons is considerably higher in upper fields than in lower grazing lands. Therefore, the production of forage biomass reduces as it move from the upper home fields in to the lower common grazing lands (Figure 4-21).

However, due to increase in the total area of grazing lands, the cumulative DM forage biomass increases as it move from the upper home fields in to the vast lower grazing lands (Figure 4-22).

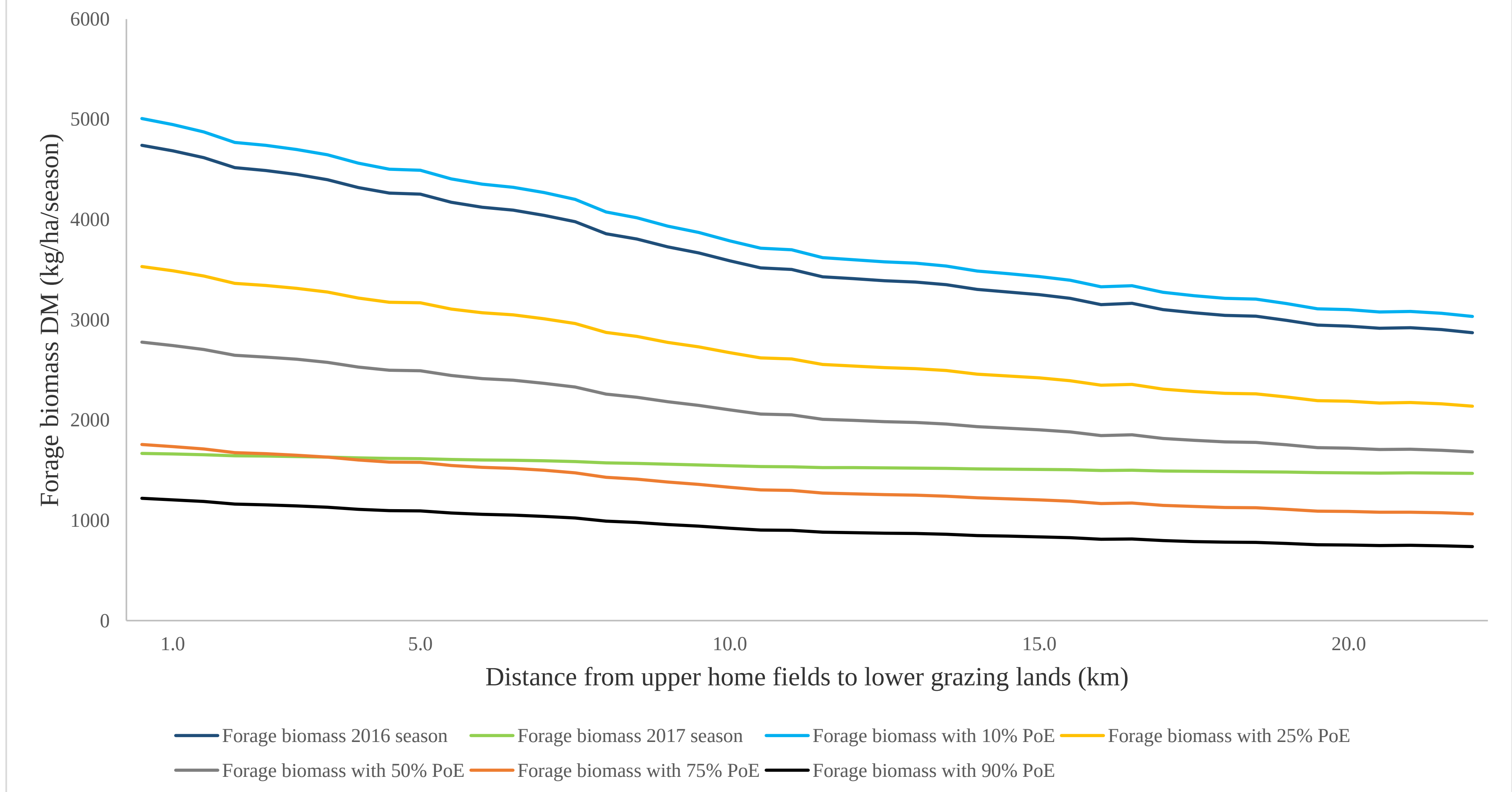


Figure 4-21: DM forage production in wet, median and dry seasons

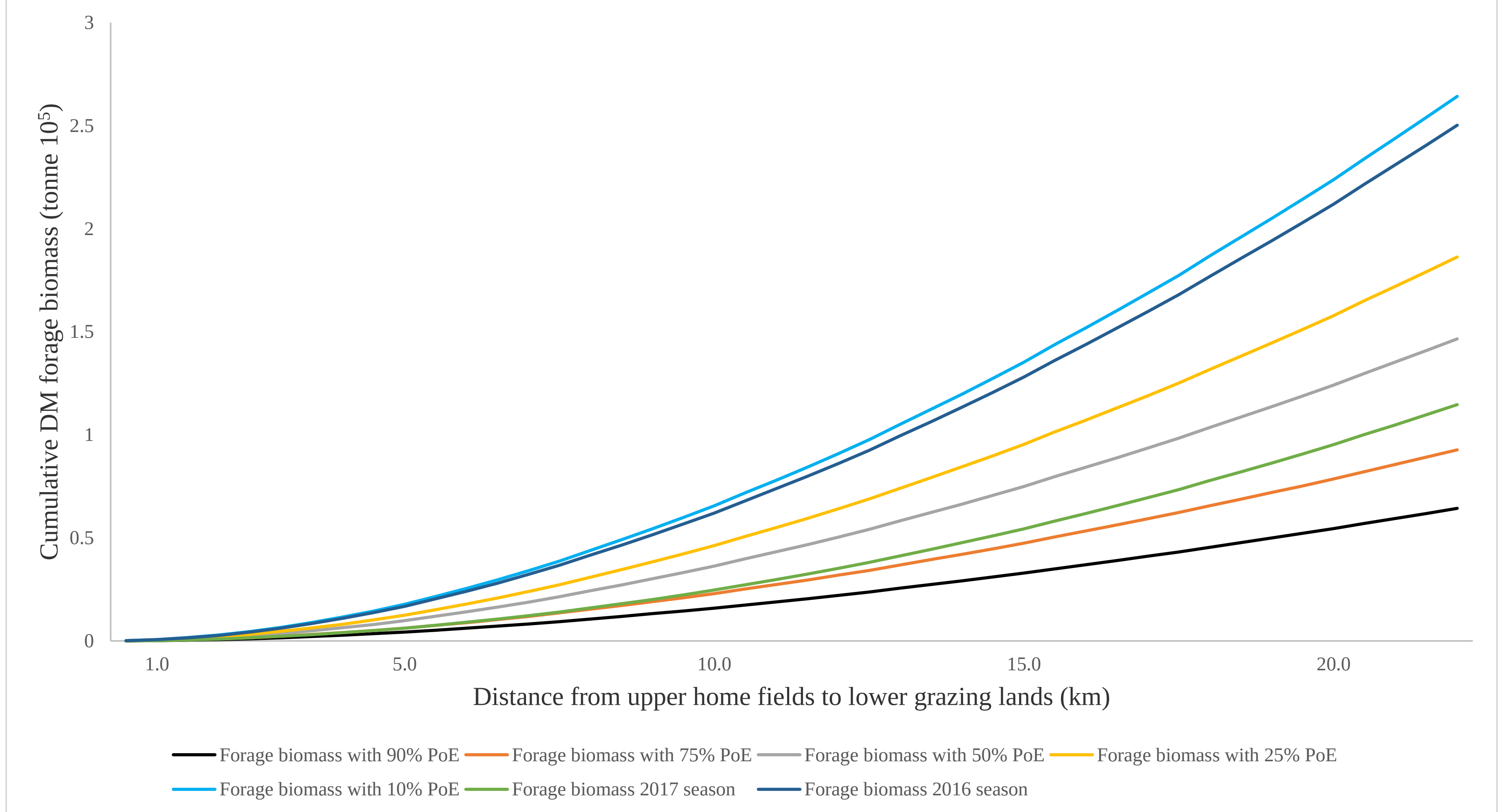


Figure 4-22: Cumulative DM forage biomass

4.3.6 Validation of the spatial rainfall and forage biomass model

The field measurements involved the total aboveground biomass, including, the herbaceous grass and the non-herbaceous shrubs in the sampled plots. The herbaceous grass biomass are palatable to livestock, while the non-herbaceous shrubs are unpalatable. The rain use efficiency used to model the forage biomass mainly considered the herbaceous grass biomass. This resulted in the differences between the measured biomass and the modelled biomass, of especially sites GLKB and GLKQ. However, the measured and the modelled forage biomass in the sites GLKB3, GLSK2, and GLSK3 are comparable. The model give conservative estimates of forage biomass production (Table 4-22).

Table 4-22: Measured and modelled forage biomass

Season	Sites	Measured DM forages (t/ha) (Means and SD)	Modelled DM forages (t/ha)	Plant forms
2016	GLKB 1	10.69(2.29)	3.50	Shrubs and grass
2016	GLKB 2	7.46(2.99)	3.40	Shrubs and grass
2016	GLKB 3	5.23(2.53)	3.39	Shrubs and grass
2016	GLKQ 1	8.16(3.24)	3.15	Shrubs and grass
2016	GLKQ 2	12.17(3.76)	3.20	Shrubs and grass
2016	GLKQ 3	7.30(1.19)	3.10	Shrubs and grass
2016	GLSK 1	6.08(0.60)	4.5	Grass
2016	GLSK 2	5.30(0.69)	4.4	Grass
2016	GLSK 3	6.73(2.87)	4.5	Grass

Values for measured forage biomass are given as mean at each site with SD in parentheses.

Additionally, the NDVI values are higher in the high altitude areas, and it reduces as it move from upper high altitude fields in to the lower grazing lands (Figure 3-7). There is also strong correlation between NDVI along 22 km transect and modelled forage biomass along the same 22 km transect (Table 4-23).

Table 4-23: Relationship between NDVI and modelled forage biomass along 22 km transect

NDVI	Modelled DM forage biomass	Correlation (R^2)
NDVI 2016	Forage biomass with 50% PoE	0.85
NDVI 2016	Forage biomass 2016 season	0.85
NDVI 2017	Forage biomass 50% PoE	0.92
NDVI 2017	Forage biomass 2017 season	0.92

Furthermore, the model showed positive relationships between altitude and rainfall. The DEM predictor impacted significantly in the rainfall predictions of all seasons. Consistently, the impact of altitude on rainfall was revealed during the field work phase of this study where rainfall had a significant positive relationship with the altitude.

Also, the real-time rainfall study showed that the season had higher rainfall in 2016 than the seasonal rainfall of 2017. The prediction of spatial model correctly revealed 2016 as a season with better rainfall and having forage biomass above average. Also, the model properly predicted the season of 2017 with low rainfall and forage biomass below average.

In the same line, the model predictions showed better quantity of forage biomass in high altitude home fields than in low-lying common grazing lands. This is in line with the land use classification of this study where good grazing lands are on high altitude areas while poor grazing lands are located in lowlands.

4.4 Discussion

Rainfall pattern in Marsabit

In Marsabit, this work is the first study deploying network of rain gauges for understanding spatial variability of rainfall. Ordinarily, rainfall collected by centralized government station is regarded as representing vast Marsabit-central sub-county and beyond. This study revealed temporal and spatial variability of rainfall. Temporally, 2016 was a season of better rain while 2017 a season of low rain (Table 4-4). Marsabit harbours different conditions of rainfall seasons. These include wet season of better rainfall, average season and a dry season of little rainfall. Additionally, both measured rainfall and spatial rainfall modelling confirmed that the fields in higher altitude areas had better rainfall than lower grazing areas. This is common in all the seasons of study. The rainfall increases with the increasing altitude. Consistent with this finding, Han, Huang et al. (2017), has also reported increase of rainfall with the altitude. This confirms that altitude can be used as a relevant predictor in rainfall modelling.

The rainfall data collected from the fields was different from the rainfall data collected by the government meteorological service. The measurement of government is close to the finding in DK location, which is situated at 4 km from government meteorological service. It is however different from other study sites, situated at 10-26 km from the meteorological service, including SG location and grazing lands (GL). The disparity between government's collected rainfall data and site-specific rainfall data increases as it move further away in to the low-lying grazing areas. Marsabit is an expansive landform made of mountains and lowlands and therefore single gauged station erected on top of Marsabit town cannot provide spatially-reliable rainfall data for Marsabit central sub-county nor for entire Marsabit County. Therefore, the prevalent practice of using single-sourced rainfall data in making land-based and development decisions in Marsabit need to be reconsidered. Modelling rainfall is an option of getting rainfall information that is spatially and temporally relevant.

Furthermore, in both years of study, over 50% of rain was received in the month of April, across the study sites. This is comparable to the data from government meteorological station which recorded 526.7 mm (88%) and 76.2 mm (50%) of rainfall in the month of April 2016 and April 2017, respectively (Table 4-5). This trend of rainfall is similar in grazing lands, where over 80% of rainfall was received in the Month of April in the year 2016. The peaking of long rains in the month of April across East African countries has been reported in other study (Ongoma and Chen 2017). Moreover, the number of days it rained ranged from 18-31 days in the upper fields and 8-19 days in the lower grazing lands (Appendix 2). In such environment, it is likely that rainfall is lost during the only month of heavy downpour. Therefore, strategies towards catching rain in the month of April is advisable option. The harvested rain can be used for supplemental irrigation and watering livestock.

Spatial modelling of rainfall: The scarcity of rainfall gauged station in arid and semi-arid areas of northern Kenya calls for innovative ideas. The modelling of rainfall provided more insights on the spatial and temporal variability of rainfall. Also, the digital elevation model (altitude) effectively predicted the spatial rainfall pattern. Other studies used only digital elevation model to predict the rainfall (Daly, Neilson et al. 1994, Arora, Singh et al. 2006). DEM, northings and eastings maps have also been used elsewhere to predict the rainfall pattern (Hutchinson 1998, Weisse and Bois 2001). Modelling of rainfall using known spatial parameters provide rainfall information where there are no rainfall gauged station. The information on rainfall can lead to the knowledge on the production of forage biomass.

Production of forage biomass: In this production system, the forage biomass in upper home fields and lower grazing lands affect the grazing pattern of cattle. The cattle in the study area grazes in lower grazing lands during rainy season. During drought or dry season, cattle are taken back to upper fields to graze in the home fields. The measured findings on the quantity of produced forages (Table 4-7, Appendix 9) is in line with other work which reported DM forage production of 6,600 to 11,000 kg/ha in south western part of Marsabit (Keya 1998). Bulle et al. (2011), also reported DM forage production ranging from 2,000 kg/ha to 17,000 kg/ha in SA and SG locations of the study. The reported findings on forage production are comparable to the results of this study.

The variability of forage biomass with rainfall is further demonstrated by the spatial model. In wet season, the model predicted DM forage production ranging from 2726 – 6317 kg/ha. This is comparable to other finding within Marsabit County which reported natural DM forages of 5,000 kg/ha in open grazing lands and DM forages of 8,000 kg/ha within natural enclosures (Oba, Vetaas et al. 2001). However, in the dry season, DM forage production was between 666 to 1,545 kg/ha. Forage production in Marsabit is variable, and it is high during better rainfall and reduces during seasons of low rainfall. This is characteristic of arid and semi-arid lands where the quantity of forage biomass follows closely the variability of rainfall.

4.5 Conclusion

Rainfall pattern in Marsabit varies with space and time. The variable rainfall has caused dissimilarities in the production of forage biomass. Furthermore, the scarcity of metereological station in Marsabit has reduced spatial relevance of government-collected rainfall data. The single-sourced rainfall data from government metereological station can not represent the variable rainfall pattern in Marsabit. The use of spatial model can provide rainfall data in places with no gauged station. The rainfall data can be turned into forage biomass by use of revealed rain use efficiency. The demonstrated information on rainfall and forage biomass can inform the decision of government and other development partners.

Chapter 5 : Soil health and crop production

5.1 Introduction

The importance of soil nutrients in supporting the global environment cannot be overemphasized. Healthy soils with adequate nutrients translate to healthy plants and animals. Soil nutrients form the basis for crops and livestock production. It also determines the existence of natural plant communities (Doran and Zeiss 2000). In addition to nutrients, the supportive function of soils depend on moisture. Soil nutrients and soil moisture plays important role in food and fibre production. In-depth research on soil nutrients and soil moisture is pre-requisite to sustainable food production in SSA.

Inadequacy of soil nutrients coupled with rainfall-dependant soil moisture reduces the food production in arid and semi-arid areas of SSA (Lal 2009). In Kenya, over 70% of landmass is either arid or semi-arid (GoK, 2011b)(Sombroek, Braun et al. 1982). In the mountainous area of Kenya's semi-arid lands, crop-livestock production system is practiced. In Marsabit-central of arid and semi-arid northern Kenya, crop-livestock agriculture provides main source of livelihoods. The communities in Marsabit-central practices the production of maize and beans, in addition to livestock keeping. The maize and beans production in Marsabit-central are under subsistence rain-fed system, and are either intercropped or grown in different fields. Maize and beans production provides human food as well as non-food crop biomass used to feed the cattle.

Although, low maize and beans productivity in this area is attributed to soil nutrients and variable moisture, the information on limiting soil nutrients is still uncertain. Similarly, there is no clear sustainability indicator that can be used to monitor food production systems in Marsabit-central. Sustainability indicators in agricultural systems provide information on the ability of a system to continue supporting growth of food and forage. The food production systems in Marsabit-central requires an indicator to measure its sustainability and monitor the trend of major soil nutrients.

The soil characteristics, soil moisture and the crop production practices in Marsabit-central were studied. This is done to disclose the current status of production, and also to recommend the scope of improving production of maize and bean crops.

This chapter addresses objective 3: *To identify the soil characteristics and crop production practices in Marsabit-central farms*

The chapter seeks to:

i. Report on the socio-economic characteristics of farming communities in Marsabit-central.
ii. Present the chemical and physical properties of soils and to specify the most limiting soil nutrient.
iii. Describe the soil moisture in different farms and along 100 mm to 1000 mm soil depths.
iv. Show maize and beans production capacity under farmer's practices
v. Report on the nitrogen fluxes in maize and beans crop fields. These include the nitrogen inputs into crop fields, nitrogen uptake by maize and bean grains and uptake by maize and beans non-food crop biomass. The nitrogen balance is also shown.
vi. Reveal manure production and its characteristics.
vii. Expound on the rain use efficiencies.
viii. Recommend usable and quantifiable sustainability indicator for Marsabit-central food production systems.

5.2 Methods of study

5.2.1 Identifying the socio-economic characteristics of farming communities

Farmer interviews

In order to understand the socio-economic characteristics of farmers in Marsabit-central, semi-structured interviews were used. In the area of study, there are four administrative locations. In each location, ten farmers practising mixed crop-livestock systems and also willing to be interviewed were purposively sampled. Total of forty farmers were interviewed over 2016 and 2017 long rain seasons. They were asked questions relating to their food production systems (Appendix 3). Farmers were asked about the number of persons living in their households, crops grown and size of land owned. Additionally, questions about the type and number of each livestock species owned were asked. Also the sources of labour for farming activities were inquired during the interview.

In addition, potential nutrient pathways within the production systems of Marsabit-central were asked and also observed. These involve identifying various subsystems within the production environment of Marsabit-central. The key materials that regulate the transfer of nutrients between the subsystems were identified with the use of farmer interviews. These include the possible sources of nitrogen for a subsystem as well as possible pathways nitrogen is taken out of a subsystem.

In the interview, the materials (wood ashes and house maintaining materials) transporting nutrients between the subsystems were further pursued. The farmers were asked about the quantity of wood ash they produces per month. Similarly, the quantity of house maintaining material (mixture of soil and manure) they use per month was also asked.

Additionally, farmers were advised to put aside wood ashes they produced. Each farmer stored wood ash in single place on top of a metal sheet. At the end of each study month, the dried wood ashes collected together by each farmer were weighed and recorded. This was done for 3 consecutive months.

5.2.2 Determining the chemical and physical characteristics of soils

The soils are ploughed using oxen during the time of sowing. The soils for chemical and physical analysis were sampled from the crop fields (Figure 5-1 and 5-2).

Figure 5-1: Image showing oxen ploughing the crop field

Figure 5-2: Image showing the crop field

Soil sampling

There are about four administratively established locations in the area of study. The human population in these locations practice crop-livestock production systems. These four locations were identified, and they include SG, BD, SA and DK (Figure 5-3).

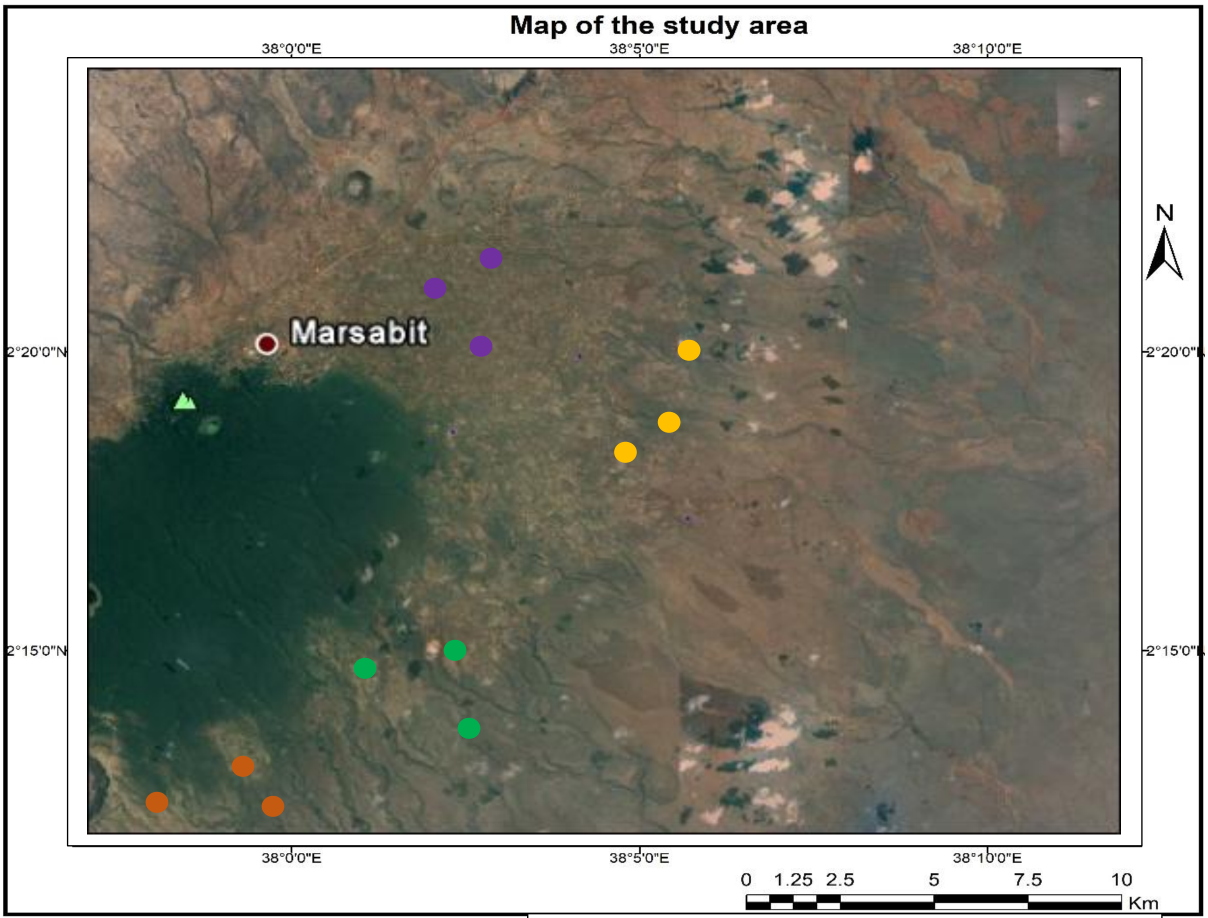


Figure 5-3: Locations of crop farms

LEGEND

- SG crop farms
- BD crop farms
- SA crop farms
- DK crop farms

In each location, 3 farms with maize and bean fields were sampled. In total, soils were sampled from 12 maize fields and 12 bean fields. Soils were sampled from two depths, including top soil (0-30 cm soil depth), and sub soil (30-60 cm soil depth).

A zig zag method was used for soil sampling. This method involved sampling soils from 10-15 points per acre (0.4 ha) per crop field. The sampling points were selected in a zig-zag positions across the entire crop field (Figure 5-4). For each crop field, soil samples for top and sub soil were collected in a different containers. The collected soil samples per crop field, were then mixed thoroughly in a container to homogenize the soils. The sub-samples of top-soils and the sub-soils were packed in a different sample bags for further analysis. These were 48 soil samples altogether.

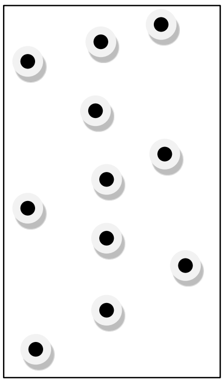


Figure 5-4: A zigzag soil sampling method

Chemical characteristics of soils

Laboratory analysis of soil samples

The soil samples were then analysed as follows:

Available P and K elements: Mehlich double acid method was used to analyse P and K. The dried soil samples (< 2 mm) at 40 ^oC were extracted in a 1:5 ratio (w/v), with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. K was determined with a flame photometer. P was determined spectrophotometrically (Mehlich 1984).

Total organic carbon: Calorimetric method was used. All organic C in the dried soil samples (< 0.5 mm) at 40 ^oC is oxidized by acidified dichromate at 150 ^oC for 30 minutes. This ensured complete oxidation. Barium chloride is added to cool the digests. After mixing thoroughly, digests were allowed to stand overnight. The C concentration is read on the spectrophotometer at 600 nm (Sims and Haby 1971, Anderson and Ingram 1993).

Total nitrogen: Kjeldahl method was used. Dried soil samples (< 0.5 mm) at 40 ^oC were digested with concentrated sulphuric acid containing potassium sulphate, selenium and copper sulphate hydrated at approximately 350 ^0C. Total N is determined by distillation followed by titration with diluted standardized 0.007144 N H_2SO_4 (Bremner and Mulvaney 1982).

Soil pH: Soil pH was determined in a 1:1 (w/v) soil – water suspension, with a pH – meter (Hesse and Hesse 1971).

Physical characteristics of soils

Soil texture was identified using hydrometer method as follows: 50 g of dried soil samples (< 2 mm) at 40 ^{o}C were weighed and transferred into a 500-ml plastic shaking bottle. 300 ml of distilled water and 50 ml of dispersion agent (calgon) were added and shaken overnight. After shaking, the soil suspension is transferred into sedimentation cylinder and topped up to the 1 L mark. It is then mixed thoroughly with a plunger to bring the soil particles into suspension. The temperature of the suspension is observed and recorded. A hydrometer is lowered into the solution and a reading taken and recorded 40 seconds after stirring ceased. After 2 hours, a second reading is taken. The first hydrometer reading gives percentage for silt and clay. The second reading gives the density of sandy particles and the percentage sand is calculated (Klute 1986).

5.2.3 Finding the soil moisture contents

Insertion of access tubes: Two locations (DK and SG) of study were identified (Figure 5-3). In each location, 3 farms with both maize and bean fields were sampled. Three 1 metre long access tubes were randomly inserted into the ground of each crop fields (Figure 5-5). A soil auguring kit was used to lead the access tubes into the ground (Figure 5-6). In DK location, 3 access tubes were inserted in to maize fields of DKMB and 3 access tubes into bean fields of DKMB. Also, 3 access tubes were inserted in to maize fields of DKJG and 3 access tubes into bean fields of DKJG. In the same location, 3 access tubes were inserted in to maize fields of DKED and 3 access tubes into bean fields of DKED.

In SG location, 3 access tubes were inserted in to maize fields of SGLK and 3 access tubes into bean fields of SGLK. Also, 3 access tubes were inserted in to maize fields of SGJL and 3 access tubes into bean fields of SGJL. In the same location, 3 access tubes were inserted in to maize fields of SGJD and 3 access tubes into bean fields of SGJD. Altogether, 36 access tubes were inserted into the crop fields for each of the long rain season of the year 2016 and 2017.

Figure 5-5: Access tube

Type: One metre long type, Manufacturer; Delta T Device company in UK.

Figure 5-6: Auguring kit

Manufacturer; Delta T Device company in UK.

Reading the soil moisture: Use of the profile probe (Figure 5-7) **and the reader** (Figure 5-8): Soil moisture readings were taken by fixing the reader into the profile probe and inserting the probe into the access tubes. The readings were taken 3 to 4 times per month, and it continued for about 4 months, a period of crop growth, from sowing up to the harvesting. The soil moisture is recorded at the following soil depths: 100 mm, 200 mm, 300 mm, 400 mm, 600 mm and at 1000 mm depth. It is read in the unit of percentage volume.

Figure 5-7: Profile probe

Type: PR1, Manufacturer; Delta T Device Company, UK.

Figure 5-8: Probe reader

Manufacturer: Delta T device company in UK.

5.2.4 Determining the yield production and crop biomass under farmer's practices

In order to understand the farmer's production systems, maize and beans production under farmer's practices were studied. This involved identifying 4 locations of study. These locations were DK, SA, BD and SG (Figure 5-3). In each location, 3 farms with both maize and bean fields were identified. The maize and bean crops were monitored throughout the growing period of 2016 and 2017 long rain seasons. At the maturity stage of each crop, 3 quadrats, each measuring 3 m x 3 m (9 m^2) were randomly sampled from maize and bean fields. The fresh crop grains and non-food crop biomass were harvested and weighed using the field balance. Samples for determining dry matter and samples for laboratory analysis were collected differently. The samples for dry matter analysis were dried in an oven at 105 ^oC for 24 hours and dry weight determined. Also, other samples were transported for laboratory analysis.

5.2.5 Quantification of nitrogen inputs and nitrogen outputs

Quantification of nitrogen inputs into the farms

The farmers whose crop production practices were studied were also interviewed. These involved 12 maize farmers and 12 bean farmers. They were interviewed during the long rain seasons of 2016 and 2017. Manure is the source of nitrogen input in to the study farms. Farmers were interviewed on the quantity of manure they applied to the crop fields per hectare per season. Wheelbarrow-load was the unit of measure used by the farmers. One standard wheelbarrow-load of manure was converted to kilogram based on the published work. In the published studies, a dried wheelbarrow load of manure was estimated at 40 kg to 50 kg (Dovie, Witkowski et al. 2003, Savala, Omare et al. 2003, Kearney, Fonte et al. 2012). For this work, an average was computed and conversion factor of 46 kg was used to get manure input in the unit of kg.

Manure used by the farmers was analysed in the laboratory and nitrogen concentrations was determined.

Laboratory analysis of nitrogen concentrations in crop grains, crop non-food biomass, forage grass and wood ash

The analysed samples include maize grains, bean grains, maize non-food biomass, beans non-food biomass, forage grass and also wood ash. Maize grains and maize non-food biomass were randomly sampled from 3 fields in every four locations (Figure 5-3). Similarly, bean grains and beans non-food biomass were also randomly sampled from 3 fields in each of the four locations of study. Forage biomass was randomly sampled from 3 sites in each of the 3 locations.

In each crop field, the samples were randomly taken from three quadrats, each measuring 3 m by 3 m (9 m^2). Therefore, in one maize field of one farm in one location, the total number of samples of maize grains were 3. This translates to 9 samples of maize grain in one location, and 36 samples of maize grain from four locations in one season. The sampling procedure is also similar for maize non-food biomass, bean grains and beans non-food biomass, and the samples were collected for two seasons of study. Forage biomass was randomly sampled from 3 quadrats, each measuring 9 m^2, in one site. The forage samples were collected from 3 sites per location, and from total of 3 locations, hence 27 samples of forage per season. Wood ash was sampled from 3 households, each household three times for two seasons.

The samples were transported from the farms and the sites of study. The samples were dried at 40 ^oC. They were then milled in preparation for laboratory analysis. In the laboratory, samples were weighed to about 50 mg (0.05g) into a foil cup. The cup is carefully folded and squashed into a pellet to expel the air using elementar. The analysis itself is carried out in CN mode, using the CN cube. This involved using a combustion, post combustion and reduction tube in the furnace of the cube analyser. The combustion tube is at 960 ^oC and a sample is dropped into this via a carousel and ball valve. Oxygen is used to burn the sample and the gas is carried off in helium through both the post combustion (900 ^oC) and reduction tubes (830 ^oC) (which are also heated) to the detectors housed within the analyser. Nitrogen element is analysed and a % figure is then obtained. Before each run, a set of standards were run which ensures that the analyser is working correctly. Standards are also run halfway through a sample run as well. To check that the analyser has performed correctly, there is a daily factor figure which is worked out after each run, this should lie between 0.9 and 1.1. Runs that do not meet the criteria are discarded.

Quantification of nitrogen output

Nitrogen output by crop (maize or bean grains) (kg/ha/season) = % N concentration in the crop grains * 10 * crop grain yields (t/ha/season)

Nitrogen output by non-food biomass (maize and beans non-food biomass) (kg/ha/season) = % N concentration in the non-food crop biomass * 10 * quantity of non-food biomass produced (t/ha/season)

Nitrogen balance

Nitrogen balance is the difference between nitrogen input and the nitrogen output. The primary nitrogen inputs and outputs were considered. The primary potential inputs were mineral fertilizer and manure, while primary potential outputs were through crop grains and non-food crop biomass. Therefore, partial nitrogen balance was calculated. The partial balance considered was at field level, involving maize and bean fields in each farm.

Partial nitrogen balance= (IN1+IN2) – (OUT1+OUT2),

Where IN1 is mineral fertilizer. Farmers interviewed showed that this is not used, hence IN1 is 0 for every crop fields. The non-use of mineral fertilizer in maize and bean fields was also confirmed by Government Ministry of Agriculture, Marsabit County.

IN2 is the nitrogen inflows through manure application to the crop fields.

OUT1= Nitrogen outflows from the fields through maize and bean grains
OUT2=Nitrogen outflows from the fields through maize and beans non-food biomass

5.2.6 Manure production by the farmers

Boma is a traditional enclosure where livestock spends at night. It is fenced with locally available woods or timbers. The floor is mainly earth and this influences the quantity of collectable manure (Figures 5-9 and 5-10). Manure for fertilization of crop fields can be collected from the livestock *boma*.

Figure 5-9: Image showing the livestock *boma*

Figure 5-10: Image showing manure in the *boma*

Cattle is the main source of manure in the study area. The manure produced by the cattle was determined as follows: *Boma* (i.e. enclosure) type that is similar to famer's *boma* was built. *Boma* size of 12.56 square metre that can occupy at least two matured zebu cattle was constructed. Just like is in the farmer's case, the floor of the *boma* is earth, and this reduces the amount of collectable manure. Two typical matured zebu cattle from the study area were allowed to graze outside in the field according to farmer's practices and taken back to the *boma* each evening at 6.30pm. In the morning at 7.30am, the manure in the *boma* was collected and fresh weight taken. The sub-sample of manure was placed in an oven for 24 hours at 105 ^{o}C and dry weight determined. The measurement of manure was done for continuous 14 days.

Additionally, 25 cattle farmers from the locations of study were also interviewed on the quantity of manure produced. The farmers gave estimates on the wheelbarrow-loads of manure produced per month. The farmers were also asked the number of cattle they own. This information was then converted to daily manure production per TLU.

The samples of cattle manure from experimental *boma* and farmer's fields were also taken and analysed in the laboratory to determine the nutrient properties.

Management of manure

Farmers in the study area stores manure at least for 4 months before applying to the crop fields, and during this period farmers store manure in the open-air ground. Therefore, six months study on manure management was conducted. The first month involved collection of manure from 3 locations of study (SG, BD and SA) (Figure 5-3), to an experimental site within Marsabit-central Sub-County. In each location, fresh manure of about 90 kg was collected from 3 different livestock *bomas*. Thus, fresh manure weighing 270 kg was collected from each location of the study. This was followed by storing manure on open area ground following farmer's practices. At the end of every study month, samples of manure were collected and analysed in the laboratory. These involve fresh manure, 1 month old to 4 months old manure. Manure of different ages were analysed for total organic carbon, total nitrogen, total phosphorous and total potassium.

Additionally, storage treatments were conducted. In this experiment, manure was stored in different ways: 1) under roof on the plastic sheet, 2) outside on the plastic sheet, 3) others, outside on the ground. The latter represent the *de facto* farmer's practice in the study area. Storage treatments were conducted for four months. After four months, manure stored differently were analysed for total organic carbon, total nitrogen, total phosphorous and total potassium.

The change in nutrient's concentrations from the time of collection (fresh manure) up to four months were considered.

Laboratory analysis of manure and house maintaining material

House maintaining material involves mixture of soil and cattle manure. The manure samples and the samples for house maintaining material were collected from three locations of study (SG, SA, BD), and three samples in each location. Also, the manure samples were collected from the manure-based experiments. The samples were then dried at 40 ^{0}C. This is followed by digestion in tubes with H_2SO_4 - salicylic acid - H_2O_2 and selenium. The larger part of organic matter is oxidised by hydrogen peroxide at relatively low temperature (100 ^{0}C). After decomposition of the excess H_2O_2 and evaporation of water, the digestion is completed by concentrated sulphuric acid at elevated temperature (330 ^{0}C) under the influence of Se as a catalyst. **Potassium** is determined with a flame photometer, **phosphorus** is determined calorimetrically on spectrophotometer, **N-total** is measured by distillation followed by titration with standardized 0.01 *N* HCl. **Total organic carbon:** Calorimetric method was used for analysing total organic carbon. The same method for soil analysis was used, as explained above in the section of methods for soil analysis (Anderson and Ingram 1993).

5.2.7 Quantifying the crop yields under manured and unmanured treatments

The purpose of this manure-based experiment was to identify the impact of manure use on the food production and also to demonstrate to farmers what local manure can do. Therefore, the experiment was laid in farmer's fields and the farmers were observing the processes from sowing to harvesting while relating the manured and the unmanured field of crops. This was done after the preliminary fieldwork revealed that utilization of manure resource in the locations of study is minimal, yet nitrogen deficiency in the soils limit the crop production.

The same four locations where farmer's crop production practices were studied were selected. These locations were DK, SA, BD and SG (Figure 5-3). Dry cattle manure was collected at no cost from the study locations. In each location, 3 farms were sampled. In each farm, 6 maize experimental plots and 6 beans experimental plots were laid.

Each experimental plot measured 5 m x 5 m (25 m^2). Experimental plots were laid in the beginning of long rain season. In the maize experimental plots, 3 plots were applied with cattle manure and 3 plots grown without manure. The rate of manure application in maize crop plots was 200 kg total nitrogen/ha. This is equivalent to 25 kg of cattle manure in one experimental plot measuring 25 m^2.

In the same line, in the beans experimental plots, 3 bean plots were applied with cattle manure and 3 bean plots without manure. The rate of manure application in bean crop plots was 100 kg total nitrogen/ha. This is equivalent to 12.5 kg of cattle manure in one experimental plot measuring 25 m^2. In the bean fields, manure was applied to provide other nutrients including P and K.

The experimental plots were then monitored throughout the growing season. At the end of growing season, experimental plots were harvested. The fresh weight of maize and bean grains and their non-food biomasses were taken in the fields. The sub-sample of grains and non-food biomass were then dried in an oven at 105 ^oC for 24 hours and dry matter recorded. Treatment effects were determined from the dry weight of total aboveground biomass and also from the dry weight of the crop grains.

5.2.8 Revealing Rain Use Efficiency (RUE) in the crop fields

RUE is the kilogram of biomass or grain yield (kg/ha) produced per unit of rain (mm). For the purpose of this study, water use efficiency is one and the same with RUE.

Rain Use Efficiency (RUE): RUE was determined from biomass or yield and rain.

It was calculated as follows:

$$\text{RUE (kg/ha/mm)} = \frac{\text{DM crop aboveground biomass or grain yield (kg/ha)}}{\text{Rainfall (mm)}}$$

Statistical analysis

R statistical software was used for analysis. Means, standard errors, and standard deviations were computed. The parameters were also subjected to non-linear model of analysis of variance (ANOVA) at 95% (P<0.05) level of confidence. Location was used as a random factor during this analysis. When ANOVA results showed significant differences, Tukey's HSD test was used to analyse the differences between the farms.

5.3 Results

5.3.1 Socio-economic factors affecting food production

The main food crops grown are maize and beans. Cattle is the main livestock while also goats and sheep production are practiced. The cattle is East African zebu and mainly of *Boran* breed. The people and the oxen provides labour for various farming activities including sowing, weeding, harvesting and transporting farm products (Table 5-1).

Table 5-1: Socio-economic characteristics of farming communities (n=40)

Number of persons living in the household (HH)[1]	Total number of persons living in one HH	6.0(1.0)
	Persons below 18 years	3.0(1.0)
	Persons above 18 years	3.0(1.0)
Land use for food production	Total land area under food production per household (ha/HH)	1.5(0.2)
	Land area under maize (*Zea mays*) cultivation (ha/HH)	0.7(0.2)
	Land area under beans (common bean) cultivation (ha/HH)	0.5(0.1)
	Land area under khat[2] *(Catha edulis forsk)* cultivation (ha/HH)	0.3(0.1)
	Home individual field area under natural forages (ha/HH)	1.0(0.3)
	Common grazing lands in the lowlands	Expansive
Livestock ownership	Number of chickens[3] owned per HH	11.0(1.0)
	Number of cattle[4] owned per HH	16.0(4.0)
	Number of goats[5] owned per HH	20.0(6.0)
	Number of sheep[5] owned per HH	11.0(3.0)
	Number of donkeys[6] owned per HH	1.0(1.0)
Sources of labour	Dominant labour during planting	People and oxen[7]
	Dominant labour during weeding	People and oxen
	Labour for fetching water	Use of donkey
Dominant time of planting in long rain seasons		Mid-April

[1]Household (HH) means people with the same head of family, and feeding from the same source.[2]Khat is a perennial shrub, leaves are chewed and it has pyscho-stimulating properties (Krizevski, Dudai et al. 2008). Farmers in Marsabit grows Khat as a cash crop. [3]Chicken is 0.01 of a TLU, [4]Cattle is one TLU, [5]Goat or sheep are 0.10 of 1 TLU, hence, 10 goats or 10 sheep are equivalent to 1 TLU, and [6]donkey is 0.5 of 1 TLU (Amadou, Dossa et al. 2012). [7]Oxen is 2 TLUs of cattle used hand-in-hand to cultivate a land. Values are means and SE in parenthesis.

5.3.2 Potential nitrogen flows in Marsabit-central food production systems

In Marsabit-central, there are various potential sources of nitrogen inflows and outflows. The nitrogen can flow to and from any of the subsystem. The subsystems include: soil and crop-farm, homestead, livestock and grazing land subsystems. Each and every subsystem affects the productivity and sustainability of every other subsystem. There are key materials that transport nitrogen nutrient to and from the subsystems. This work quantified the key materials marked in brown colour (Figure 5-11).

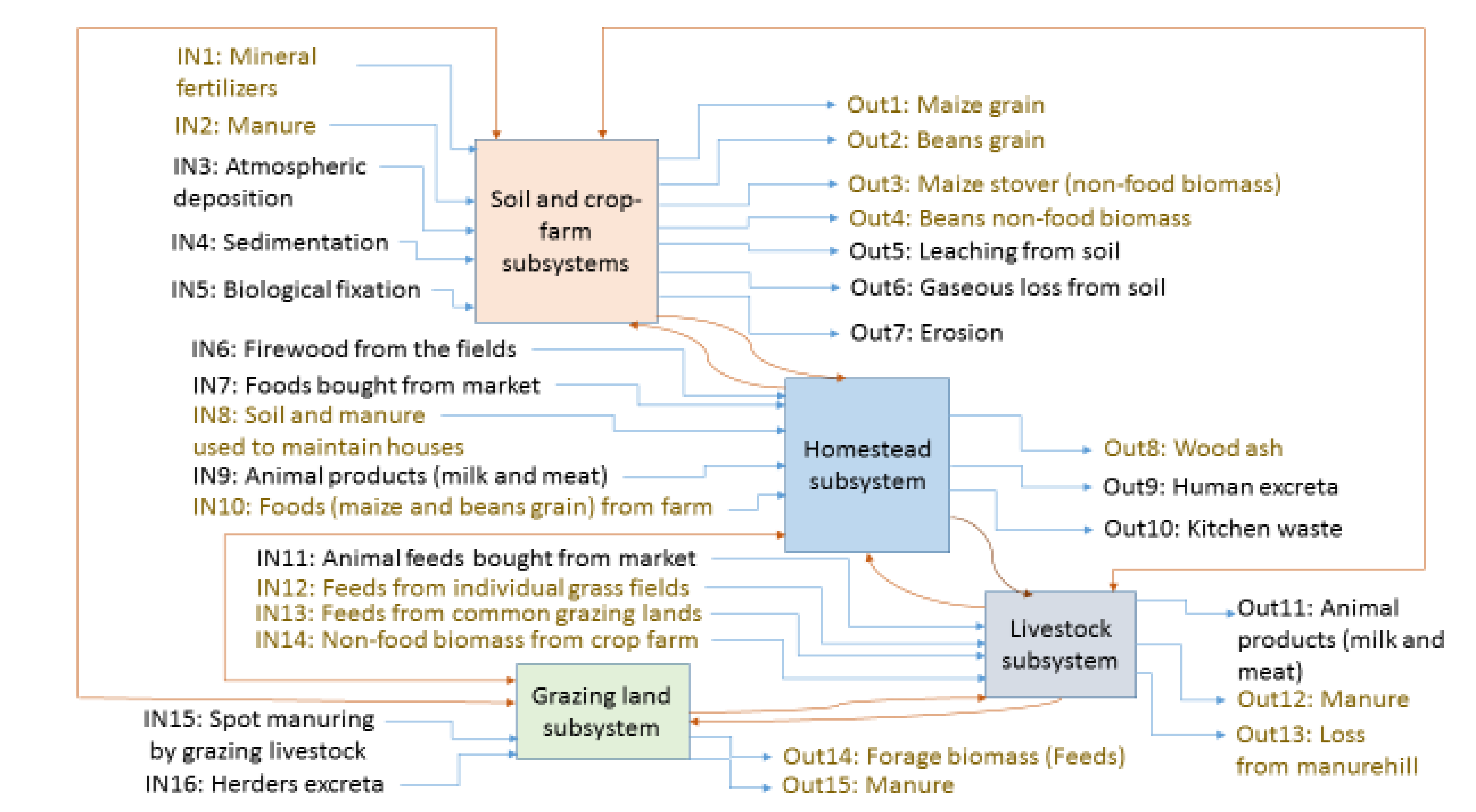


Figure 5-11: Potential nitrogen pathways within Marsabit-central food production systems

5.3.3 Nitrogen concentrations in the key materials

The key materials flowing to and from the subsystems carry nitrogen, in addition to other nutrients. Excessive outflow of nitrogen from a subsystem results in deficient nitrogen in the same subsystem. However, excessive inflow of nitrogen element into a subsystem results in unnecessary accumulation of nitrogen in the same subsystem. The nitrogen inflows and outflows need to be balanced. The balanced nitrogen in Marsabit-central food production systems depend on the synchronized management of the key materials (Table 5-2).

Table 5-2: Nitrogen concentrations in the key materials flowing between the subsystems

Key materials	Total nitrogen concentrations in the key materials (%)[1]	n=	Average quantity of materials produced or used during the year 2016 and 2017	Source
	Means and SD			
Maize grains	1.54(0.55)	94	1070 kg/ha of dry maize grain produced per season	Own work
Maize non-food biomass	1.34(0.97)	109	5850 kg/ha of dry maize non-food biomass produced per season	Own work
Bean grains	4.01(0.92)	131	680 kg/ha of dry beans grain produced per season	Own work
Bean non-food biomass	1.80(0.99)	109	1020 kg/ha of dry beans non-food biomass produced per season	Own work
Material for maintaining houses (mixture of soil and livestock manure)	1.75(0.35)	3	32 kg of dry material mixture used per house per month	Own work
Forage grass (Livestock feeds)	0.98(0.71)	9	6000 kg/ha of dry forages produced in wet season	Own work
Wood ash	0.13(0.06)	9	8 kg of dry ashes produced per household per month	Own work
Cattle manure	2.22(0.54)	20	1.71 kg of dry manure produced per day per TLU	Own work

[1]The reported total nitrogen concentrations and quantity of material produced or used are mean of each material with SD in parentheses.

5.3.4 Chemical and physical characteristics of soils

Chemical characteristics of soils

The average pH is 6.3 and 6.1 for top and sub soil, respectively. Also, the average total nitrogen is 0.13% and 0.12% for top and sub soil, respectively. The soil nitrogen is low across the locations of the study and across the soil depths (Table 5-3).

Physical characteristics of soils

The soil texture is dominated by clay, followed by silt and lastly sand (Table 5-4). All the soils of four locations of study are classified as clay soils.

The chemical and physical properties of soils are generally similar among all the four locations of study. Thus, similar nutrient management measures across the four locations can solve the nitrogen limitations.

Table 5-3: Chemical characteristics of soils (n=48)

	BD location	DK location (Means and SE)	SA location	SG location	Deficiency level for chemical characteristics	Sources for deficiency level
Soil depth (cm)	**pH**	**pH**	**pH**	**pH**		
0-30 (Topsoil)	6.6(0.15)a	6.1(0.06)b	6.1(0.02)b	6.2(0.11)b	<5.5	Adapted from: (Muya, Gitau et al. 2010, Berazneva, McBride et al. 2016)
30-60 (Subsoil)	6.3(0.16)b	6.1(0.07)b	6.0(0.05)b	6.1(0.10)b		
	Total N (%)	**Total N (%)**	**Total N (%)**	**Total N (%)**		
0-30 (Topsoil)	0.12(0.020)a	0.12(0.005)a	0.13(0.003)a	0.13(0.007)a	<0.20%	Adapted from: (Muya, Gitau et al. 2010, Berazneva, McBride et al. 2016)
30-60 (Subsoil)	0.12(0.007)ab	0.10(0.007)b	0.13(0.005)a	0.13(0.005)a		

Means in each row that do not share a letter are significantly different at $P \leq 0.05$ by Tukey's HSD test. Values are given as mean at each location with SE in parentheses.

Table 5-3 …………….. Continued

	BD location	DK location	SA location	SG location	Deficiency level for chemical characteristics	Sources for deficiency level
			(Means and SE)			
Soil depth (cm)	**Available P (ppm)**	**Available P (ppm)**	**Available P (ppm)**	**Available P (ppm)**		
0-30 (Topsoil)	33.33(5.43)a	54.17(11.93)a	52.50(14.24)a	19.17(4.36)a	<20.00 ppm	Adapted from: (Muya, Gitau et al. 2010)
30-60 (Subsoil)	20.83(2.01)b	31.67(9.46)b	40.83(10.44)b	27.50(3.82)b		
	Available K (%)	**Available K (%)**	**Available K (%)**	**Available K (%)**		
0-30 (Topsoil)	1.09(0.11)a	1.09(0.06)a	0.99(0.06)a	0.88(0.20)a	<0.83%	Adapted from: (Muya, Gitau et al. 2010)
30-60 (Subsoil)	0.76(0.19)b	0.62(0.08)b	0.64(0.02)b	0.62(0.15)b		
	Total C (%)	**Total C (%)**	**Total C (%)**	**Total C (%)**		
0-30 (Topsoil)	1.23(0.23)a	1.02(0.06)a	1.37(0.04)a	1.37(0.12)a	<1.08%	Adapted from: (Muya, Gitau et al. 2010)
30-60 (Subsoil)	1.11(0.13)ab	0.73(0.09)b	1.17(0.05)a	1.15(0.10)a		

Means in each row that do not share a letter are significantly different at $P \leq 0.05$ by Tukey's HSD test. Values are given as mean at each location with SE in parentheses.

Table 5-4: Physical characteristics of soils (n=48)

	BD location	DK location	SA location	SG location
		(Means and SE)		
Soil depth (cm)	**Clay (%)**	**Clay (%)**	**Clay (%)**	**Clay (%)**
0-30 (Topsoil)	64.67(3.53)b	67.67(1.31)b	62.00(3.61)b	69.33(1.69)b
30-60 (Subsoil)	72.00(3.22)a	73.33(1.69)a	71.67(1.58)a	75.33(0.99)a
	Silt (%)	**Silt (%)**	**Silt (%)**	**Silt (%)**
0-30 (Topsoil)	22.00(1.71)a	21.67(1.41)a	21.00(1.34)a	22.33(1.50)a
30-60 (Subsoil)	15.33(0.99)a	18.67(2.17)a	19.00(1.69)a	19.00(1.00)a
	Sand (%)	**Sand (%)**	**Sand (%)**	**Sand (%)**
0-30 (Topsoil)	13.33(1.84)ab	10.67(0.84)ab	17.00(3.61)a	8.33(0.80)b
30-60 (Subsoil)	12.67(2.35)a	8.00(1.46)ab	9.33(0.84)ab	5.67(1.41)b

Means in each row that do not share a letter are significantly different at $P \leq 0.05$ by Tukey's HSD test. Values are given as mean at each location with SE in parentheses.

5.3.5 Soil moisture dynamics within the farms of Marsabit-central

The farms in SG location had average soil moisture of 33.03% and 33.23% for the seasons of 2016 and 2017, respectively. However, the farms in DK location had average soil moisture of 22.87% and 20.27% for the seasons of 2016 and 2017, respectively. The farms in SG location had better soil moisture for two seasons than the farms in DK location. Farms in same location, mainly had no significant differences in soil moisture ($P \leq 0.05$) (Figure 5-12 and Figure 5-13).

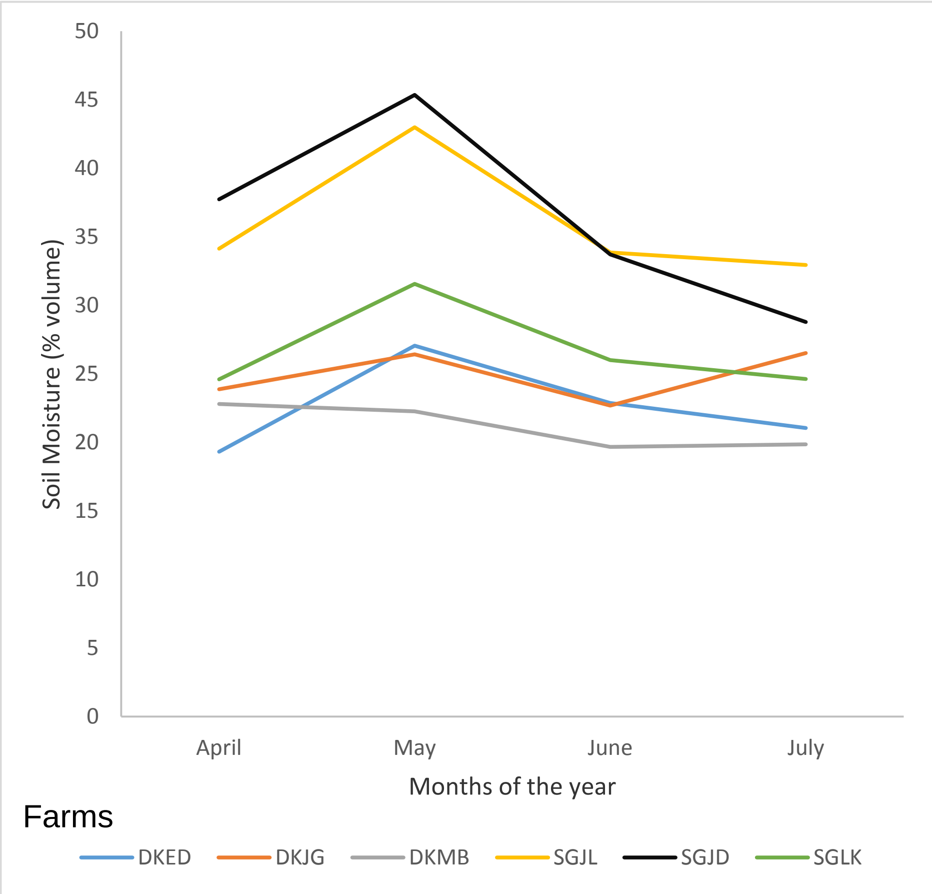
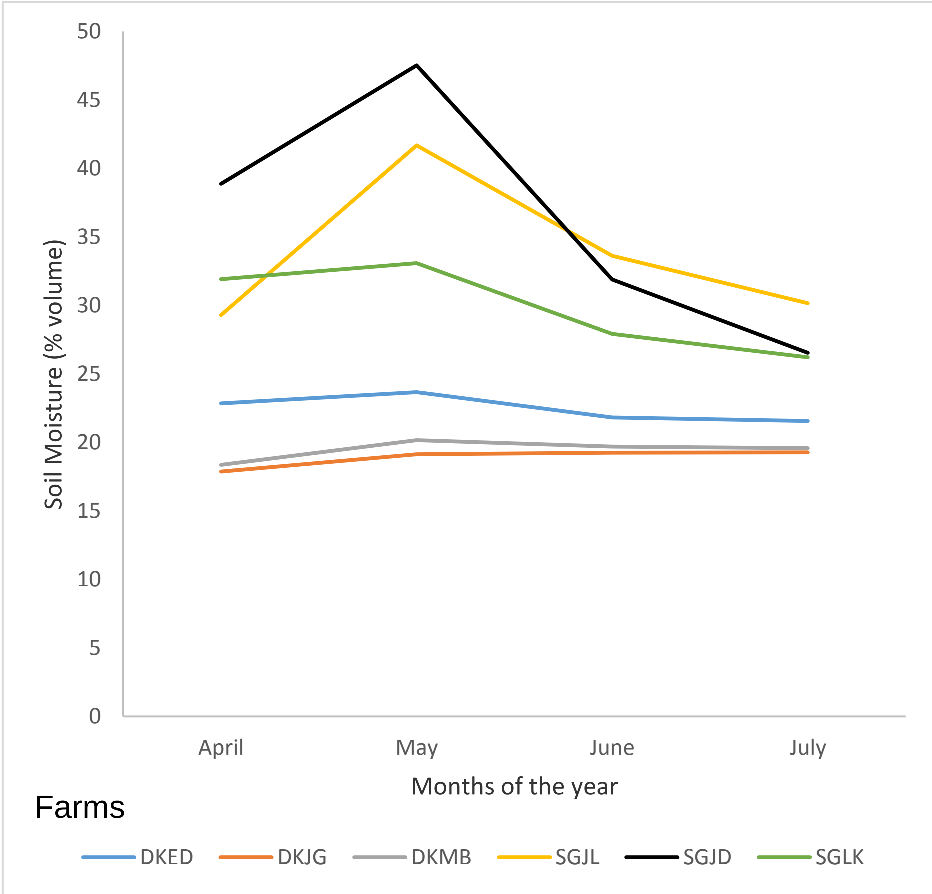
	

Figure 5-12: Soil moisture of the farms in the season 2016	Figure 5-13: Soil moisture of the farms in the season 2017

The beans and maize fields did not differ significantly in terms of soil moisture (Table 5-5). This is understandable because both beans and maize fields are in the same individual farm, having same amount of rainfall and similar field's management practices.

Table 5-5: Soil moisture in beans and maize fields (n=36)

	Soil moisture (% volume)	Soil moisture (% volume)
Months	Bean fields	Maize fields
	(Means and SE)	(Means and SE)
April 2016	26.36(1.92)a	27.80(2.11)a
April 2017	25.92(1.77)b	27.13(2.13)b
May 2016	32.88(2.30)a	32.55(2.40)a
May 2017	30.97(2.10)d	30.77(2.32)d
June 2016	26.83(1.99)a	26.34(2.17)a
June 2017	26.16(2.02)a	25.24(2.10)a
July 2016	25.76(1.87)a	25.54(2.12)a
July 2017	24.38(1.97)a	23.40(1.94)a

Means in each row that do not share a letter are significantly different at $P \leq 0.05$ by Tukey's HSD test. Values are given as mean for each month with SE in parentheses.

Soil moisture along the soil depths

Soil moisture increases with the increasing soil depth. The average moisture along the soil depths include the following: 100mm-12.69%, 200mm-15.06%, 300mm-21.13%, 400mm-31.94%, 600mm-38.67%, and 1000mm-53.88%. Better soil moisture are found between 400 mm to 1000 mm soil depths across the study farms. Also, in both seasons of study, the soil moisture start increasing from month of April and peaks in the month of May. This is following downpour of rain in the month of April. From the period of mid-May, as rainfall intensity reduces and sun sets in, the soil moisture reduces across various soil depths (Figure 5-14 and Figure 5-15).

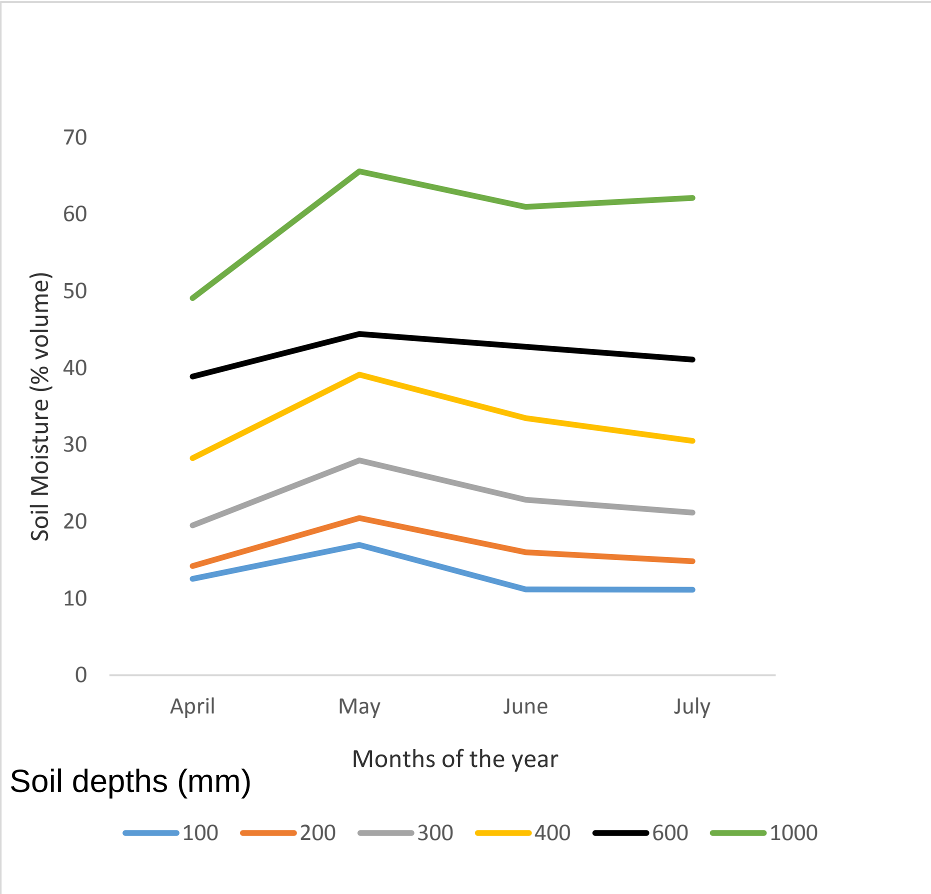
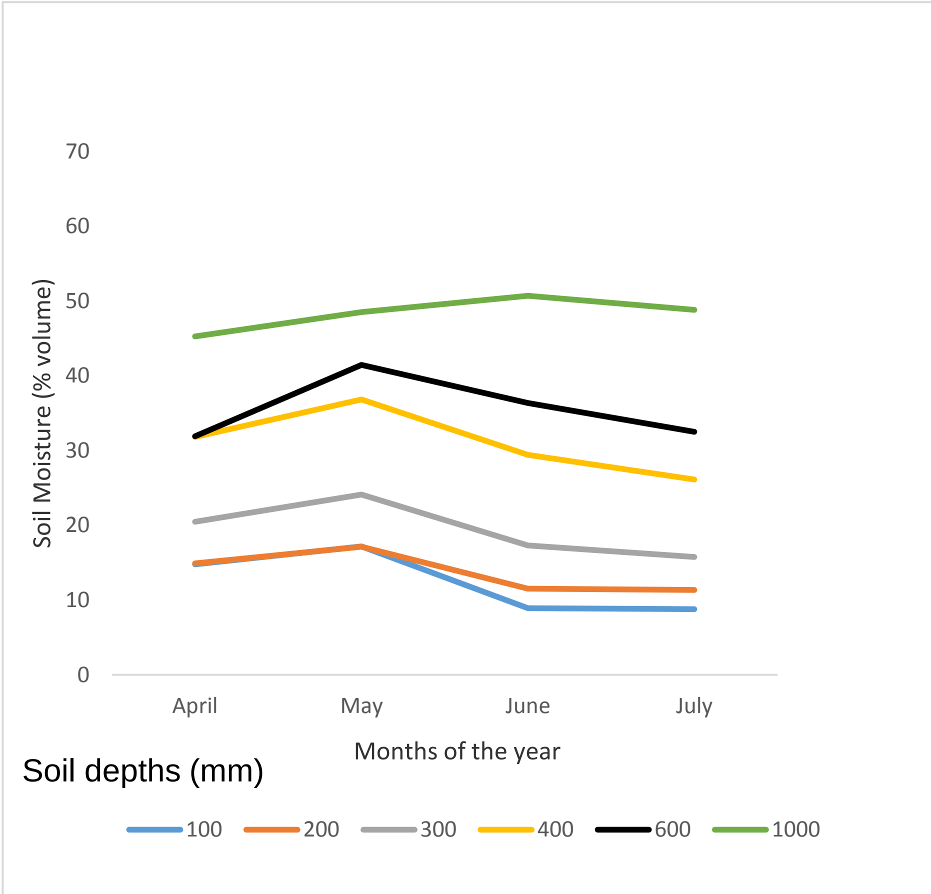
	

Figure 5-14: Soil moisture along the soil depths in the season of 2016	Figure 5-15: Soil moisture along the soil depths in the season of 2017

5.3.6 Crop grain yields and aboveground biomass production under farmer's practices

5.3.6.1 Crop grain yields in different farms

The maize grain yields in the season of 2016 varied from 0.45 to 3.35 t/ha, with an average yield of 1.27 t/ha. In the season of 2017, the average maize grain yield was 0.87 t/ha, ranging from 0.14 to 1.46 t/ha. The maize grain yields for the seasons of 2016 and 2017 differed significantly among the farms ($P \leq 0.05$).

The farms recorded average beans grain yield of 0.80 t/ha in the season of 2016. In this season, the bean grain yields ranged from 0.11 to 1.46 t/ha. However, in the season of 2017, the average beans grain yield was 0.57 t/ha, varying from 0.42 to 0.75 t/ha. There were significant differences among the bean yields ($P \leq 0.05$). The maize and bean grain yields were higher in the season of 2016 than the season of 2017 (Table 5-6 and Table 5-7).

Table 5-6: Maize and beans grain yields of season 2016 (n=12)

Locations	Farms	DM maize grain yields t/ha (Means and SD)	DM beans grain yields t/ha (Means and SD)
DK	DKED	2.29(0.38)	1.15(0.28)
	DKJG	3.35(0.48)	1.37(0.49)
	DKMB	0.92(0.00)	1.32(0.00)
SG	SGJL	1.61(1.59)	0.20(0.09)
	SGJD	0.72(0.36)	0.78(0.60)
	SGLK	1.59(0.56)	1.46(0.00)
SA	SABD	1.09(0.54)	0.26(0.21)
	SAHS	0.68(0.00)	0.11(0.00)
	SAKT	0.59(0.00)	0.94(0.00)
BD	BDDT	0.45(0.27)	0.19(0.10)
	BDMG	1.07(0.46)	1.43(0.48)
	BDNW	0.91(0.39)	0.42(0.32)

Values are given as mean at each farm with SD in parentheses.

Table 5-7: Maize and beans grain yields of season 2017 (n=5)

Locations	Farms[1]	DM maize grain yields t/ha (Means and SD)	DM beans grain yields t/ha (Means and SD)
SG	SGJL	0.14(0.05)	0.64(0.20)
	SGJD	0.86(0.16)	0.42(0.09)
	SGLK	1.46(0.62)	0.61(0.23)
BD	BDDT	1.11(0.25)	0.44(0.11)
	BDMG	0.76(0.28)	0.75(0.27)

Values are given as mean at each farm with SD in parentheses. [1]The low rainfall in 2017 meant that the crop grain yields were not measurable in some of the study farms.

5.3.6.2 Crops total aboveground biomass in different farms

The total aboveground biomass also shows significant differences across the farms ($P \leq 0.05$). The total aboveground biomass is addition of crop grain yields and non-food crop biomass. However, the latter is more in quantity and is used to feed the livestock. The maize total aboveground biomass ranges from 2.78-11.14 t/ha and from 1.45-7.52 t/ha in the seasons of 2016 and 2017, respectively. The beans total aboveground biomass ranges from 0.69-4.00 t/ha and from 0.39-3.40 t/ha in the seasons of 2016 and 2017, respectively (Table 5-8).

Table 5-8: Maize and beans total aboveground biomass in different farms (n=12)

		2016 season	2017 season	2016 season	2017 season
Locations	Farms	Maize total aboveground biomass DM t/ha (Means and SD)	Maize total aboveground biomass DM t/ha (Means and SD)	Beans total aboveground biomass DM t/ha (Means and SD)	Beans total aboveground biomass DM t/ha (Means and SD)
DK	DKED	11.14(1.48)	4.03(0.90)	3.49(0.50)	0.94(0.16)
	DKJG	9.61(2.54)	4.05(0.90)	3.41(0.48)	0.39(0.14)
	DKMB	2.78(1.06)	1.45(0.45)	3.16(0.00)	0.58(0.18)
SG	SGJL	8.52(7.20)	1.59(0.73)	0.69(0.30)	1.33(0.28)
	SGJD	10.72(2.68)	4.42(1.42)	3.52(1.93)	0.61(0.22)
	SGLK	8.06(2.96)	7.52(1.99)	4.00(0.56)	1.71(0.42)
SA	SABD	3.12(1.56)	1.50(0.53)	1.05(0.02)	0.55(0.32)
	SAHS	3.78(0.52)	2.22(0.64)	1.14(0.12)	1.09(0.38)
	SAKT	3.99(0.49)	1.86(0.49)	2.13(0.40)	0.61(0.19)
BD	BDDT	6.12(1.21)	5.48(2.11)	1.09(0.27)	1.99(0.55)
	BDMG	10.92(1.51)	5.97(2.28)	3.33(1.05)	3.40(0.88)
	BDNW	6.76(0.93)	6.82(0.79)	1.45(0.21)	2.59(0.02)

Values are given as mean at each farm with SD in parentheses.

5.3.7 Nitrogen flows in the crop fields

5.3.7.1 Nitrogen inputs and the nitrogen outputs

The predominant source of nitrogen input is through manure. This work did not find the use of mineral fertilizer in the food crop fields of study area.

The nitrogen removal by maize stover (non-food biomass) is higher than the nitrogen removal by maize grains. This is due to higher quantity of non-food maize biomass produced more than the crop-grain itself. The non-food crop biomass forms part of livestock feed.

Unlike maize, nitrogen removal by bean grains is higher than removal by bean non-food biomass. This is due to higher nitrogen concentrations in bean crop grains than non-food bean biomass (Table 5-9).

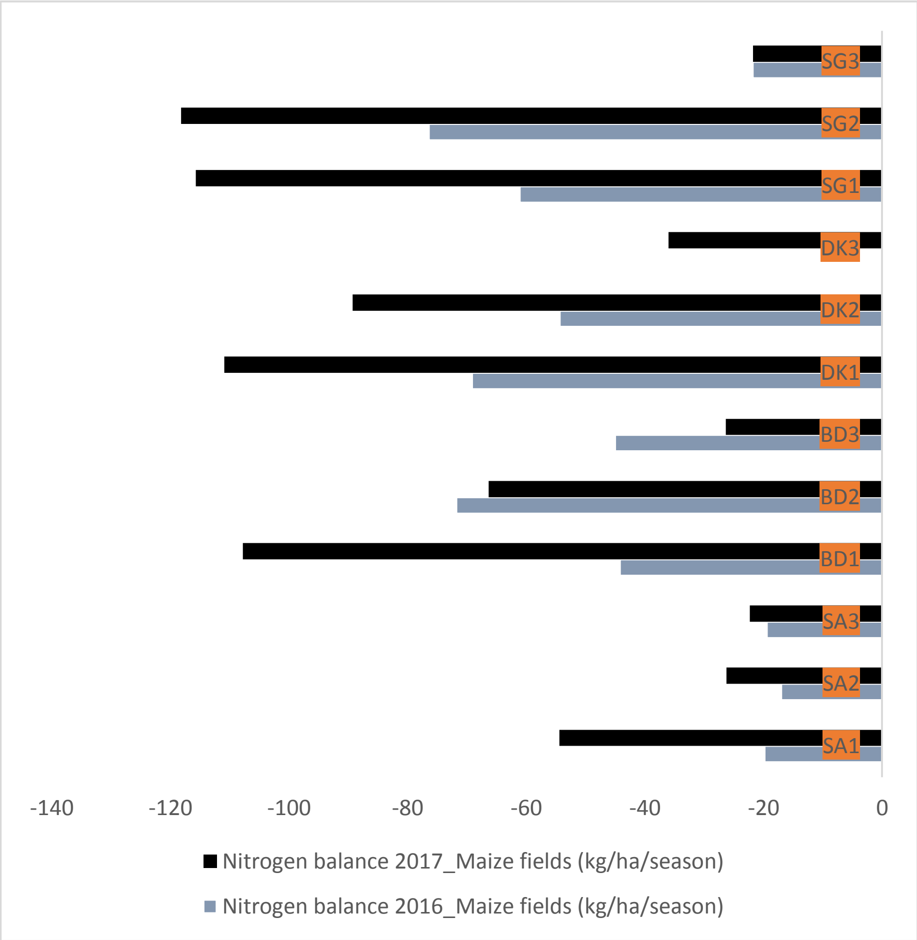
Generally, the nitrogen inflows through manure is less than the summation of nitrogen offtake by crop grains and non-food crop biomass. This results in negative nitrogen balance.

Table 5-9: Nitrogen inputs and nitrogen outputs in Marsabit-central crop fields (n=12)

		Maize fields				Bean fields			
		2016 season		2017 season		2016 season		2017 season	
Locations	Farms	Nitrogen removal by maize grains and maize non-food biomass (kg/ha)	Nitrogen input into maize fields by manure (kg/ha)	Nitrogen removal by maize grains and maize non-food biomass (kg/ha)	Nitrogen input into maize fields by manure (kg/ha)	Nitrogen removal by bean grains and non-food bean biomass (kg/ha)	Nitrogen input into bean fields by manure (kg/ha)	Nitrogen removal by bean grains and non-food bean biomass (kg/ha)	Nitrogen input into bean fields by manure (kg/ha)
DK	DK1	78.27	9.11	115.50	4.55	48.25	4.55	49.82	4.55
	DK2	68.05	13.67	92.00	2.73	60.79	9.11	23.87	2.73
	DK3	18.42	18.22	38.77	2.73	49.03	13.66	15.17	1.82
SG	SG1	74.77	13.66	133.92	18.22	10.33	13.66	60.15	18.23
	SG2	79.19	2.73	145.43	27.22	62.66	1.82	30.83	18.23
	SG3	67.37	45.54	40.01	18.22	70.20	45.54	46.44	18.22
SA	SA1	24.37	4.55	59.60	5.19	37.46	4.55	17.83	5.19
	SA2	26.12	9.11	36.26	10.02	10.95	9.11	17.39	6.38
	SA3	28.57	9.11	27.52	5.19	14.92	9.11	23.29	5.19
BD	BD1	51.49	7.29	118.73	10.93	15.61	6.38	69.91	7.29
	BD2	80.90	9.11	75.46	9.11	23.82	13.66	62.84	5.46
	BD3	54.15	9.11	33.66	7.29	75.69	2.73	42.30	4.55

5.3.7.2 Nitrogen balance

The maize fields recorded nitrogen balance ranging from -0.2 to -76.5 kg/ha/season and from -21.8 to -118.2 kg/ha/season in the seasons of 2016 and 2017, respectively. The bean fields recorded nitrogen balance ranging from 3.3 to -72.9 kg/ha/season and from -11.0 to -62.6 kg/ha/season in the seasons of 2016 and 2017, respectively. The average nitrogen balance in the maize fields was -41.7 and -66.3 kg/ha/season for the seasons of 2016 and 2017, respectively. Also, the average nitrogen balance in the bean fields was -28.8 and -30.2 kg/ha/season for the seasons of 2016 and 2017, respectively (Figure 5-16 and Figure 5-17).



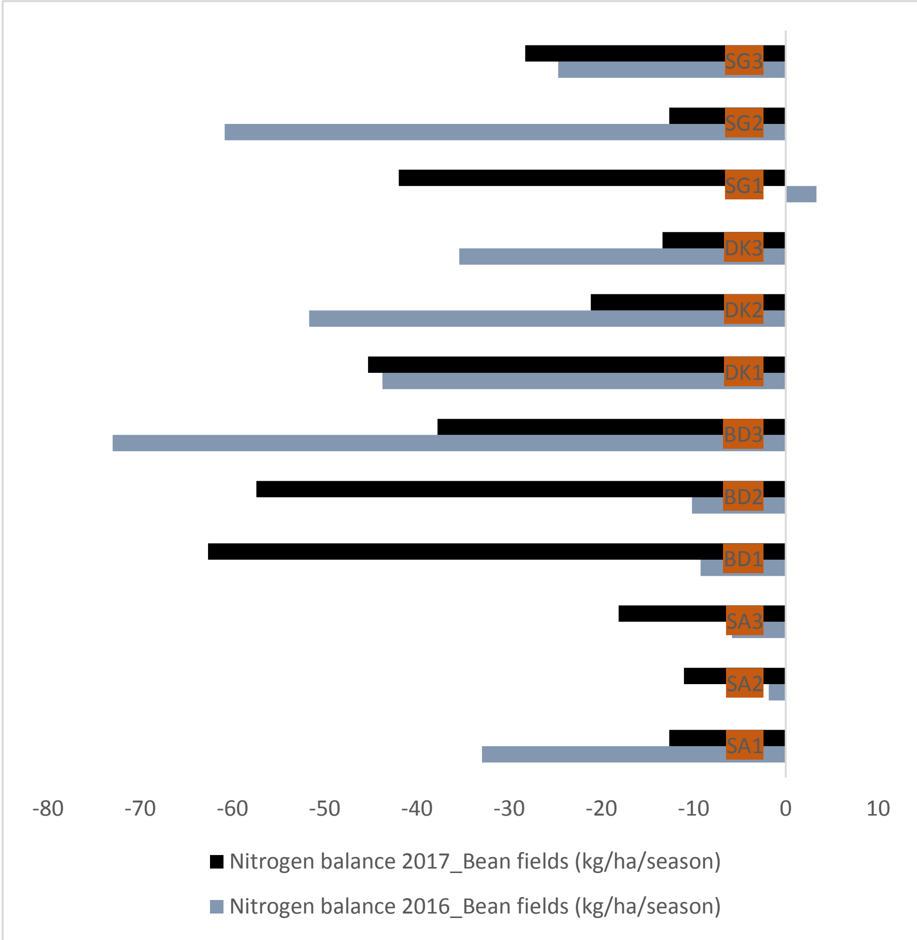


Figure 5-16: Nitrogen balance in maize fields	Figure 5-17: Nitrogen balance in bean fields

5.3.8 Manure production and its chemical characteristics

The manure production was 1.71±0.1 kg DM manure per day per TLU. There were no significant differences in the chemical compositions of manure among various locations (Table 5-10).

Table 5-10: Chemical characteristics of dry manure (n=9)

Locations	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
		(Means and SD)		
SG	7.41(2.33)	2.28(0.66)	0.42(0.13)	1.14(0.69)
SA	7.20(1.92)	2.28(0.69)	0.34(0.15)	1.30(0.92)
BD	7.08(2.33)	2.16(0.34)	0.36(0.08)	0.97(0.60)

Values are given as mean at each location with SD in parentheses.

Age had significant impact on the total organic carbon, total phosphorous and total potassium while showing trend with the total nitrogen of manure (Table 5-11).

Table 5-11: Age affecting quality of manure (n=12)

Age of manure	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
		(Means and SE)		
4 months	5.79(0.34)b	1.98(0.10)a	0.33(0.04)b	0.63(0.12)b
2 months	5.84(0.42)b	1.98(0.08)a	0.42(0.02)ab	1.64(0.21)a
One month	5.92(0.55)b	2.10(0.15)a	0.42(0.03)ab	1.95(0.21)a
Fresh manure	8.66(0.62)a	2.49(0.21)a	0.53(0.03)a	2.50(0.27)a
ANOVA effect age (*P* value)	<0.001	0.052	0.005	<0.001

Means in each column that do not share a letter are significantly different at $P \leq 0.05$, by Tukey's HSD test. Values are given as mean for each month with SE in parentheses.

5.3.8.1 Storage of manure

There were no significant differences in the chemical compositions of manure stored differently (Table 5-12). Storage treatments did not have any significant effect.

Table 5-12: Methods of manure storage (n=9)

Treatments	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
		(Means and SE)		
Manure stored outside on the ground	5.99(0.15)	2.22(0.15)	0.47(0.04)	2.09(0.22)
Manure stored outside on the plastic sheet	6.34(0.29)	2.57(0.48)	0.38(0.02)	2.18(0.30)
Manure stored on the plastic sheet + under roof	6.90(0.46)	2.16(0.19)	0.39(0.04)	2.48(0.19)
ANOVA Effect of storage methods (*P* – value)	0.056	0.515	0.109	0.495

Values are given as mean for each treatment with SE in parentheses.

5.3.9 Crops production under manure treatment

The soils in the study area responded positively to the manure treatment. The crop grain yields and aboveground crop biomass were higher in the manured fields (Table 5-13). However, the year 2017 season was of low rainfall below the median and crops production was affected by the rainfall.

Table 5-13: Maize and beans production in manured and unmanured fields (n=12)

Maize production			Beans production		
Manure treatments	Maize grain yields DM t/ha (Means and SE)	Total aboveground maize biomass DM t/ha (Means and SE)	Manure treatments	Beans grain yields DM t/ha (Means and SE)	Total aboveground beans biomass DM t/ha (Means and SE)
200 kg N/ha	1.70(0.23)a	4.42(0.43)a	100 kg N/ha	0.92(0.04)a	2.56(0.17)a
0 kg N/ha	0.65(0.09)b	2.87(0.34)b	0 kg N/ha	0.59(0.08)b	1.44(0.12)b

Means in each column that do not share a letter are significantly different at $P \leq 0.05$, by Tukey's HSD test. Values are given as mean for each treatment with SE in parentheses.

5.3.10 Rain Use Efficiency (RUE) in the crop fields

5.3.10.1 Rain Use Efficiency (RUE) of crop grain yields under farmer's practices

The farms recorded average RUE of 2.39 kg/ha/mm for maize grains in the season of 2016, with RUE ranging from 0.79 to 5.77 kg/ha/mm. Also, in the season of 2017, the average RUE of maize grains was 2.97 kg/ha/mm, varying from 0.45 to 4.61 kg/ha/mm.

In the season of 2016, the average RUE of bean grains was 1.54 kg/ha/mm, and it ranged from 0.19 to 3.24 kg/ha/mm. The bean grains had average RUE of 2.23 kg/ha/mm for the season of 2017, and it varied from 1.64 to 2.79 kg/ha/mm. The RUE in the farms significantly differed owing to differences in the rainfall (Table 5-14 and Table 5-15).

Despite the lesser rainfall received in the season of 2017, both maize and bean grains showed better RUE in the season of 2017 than the season of 2016.

Table 5-14: RUE for maize and bean grains during 2016 season (n=12)

Locations	Farms	RUE for maize grains (kg/ha/mm) (Means and SD)	RUE for bean grains (kg/ha/mm) (Means and SD)
DK	DKED	3.99(0.67)	2.00(0.50)
	DKJG	5.77(0.83)	2.36(0.85)
	DKMB	1.68(0.00)	2.42(0.00)
SG	SGJL	3.14(3.11)	0.39(0.17)
	SGJD	1.46(0.72)	1.58(1.21)
	SGLK	3.50(1.24)	3.24(0.00)
SA	SABD	2.24(1.11)	0.46(0.36)
	SAHS	1.39(0.00)	0.19(0.00)
	SAKT	1.20(0.00)	1.66(0.00)
BD	BDDT	0.79(0.48)	0.40(0.20)
	BDMG	1.88(0.82)	2.96(0.99)
	BDNW	1.60(0.69)	0.86(0.65)

Values are given as mean at each farm with SD in parentheses.

Table 5-15: RUE for maize and bean grains during 2017 season (n=5)

Locations	Farms	RUE for maize grains (kg/ha/mm)	Farms	RUE for bean grains (kg/ha/mm)
		(Means and SD)		(Means and SD)
SG	SGJL	0.45(0.16)	SGJL	2.11(0.66)
	SGJD	2.82(0.53)	SGJD	2.71(0.62)
	SGLK	4.61(1.97)	SGLK	1.93(0.72)
BD	BDDT	4.14(0.93)	BDDT	1.64(0.42)
	BDMG	2.83(1.04)	BDMG	2.79(0.99)

Values are given as mean at each farm with SD in parentheses.

5.3.10.2 Rain Use Efficiency (RUE) of crop's total aboveground biomass under farmer's practices

The RUE was between 5.06 to 21.61 kg/ha/mm for maize total aboveground biomass and 1.37 to 8.85 kg/ha/mm for total bean aboveground biomass, in the season of 2016. However, in the season of 2017, the RUE ranged from 5.22 to 27.09 kg/ha/mm for maize total aboveground biomass and 2.00 to 12.72 kg/ha/mm for total bean aboveground biomass.

The RUE for total maize and bean aboveground biomass differed significantly among the farms ($p \leq 0.05$). Also, the RUE of total aboveground biomass was higher in the season of 2017 than in the season of 2016 (Table 5-16).

Table 5-16: RUE for maize and beans total aboveground biomass in different farms (n=12)

		2016 season	2017 season	2016 season	2017 season
Locations	Farms	Maize total aboveground biomass RUE (kg/ha/mm)	Maize total aboveground biomass RUE (kg/ha/mm)	Beans total aboveground biomass RUE (kg/ha/mm)	Beans total aboveground biomass RUE (kg/ha/mm)
		(Means and SD)	(Means and SD)	(Means and SD)	(Means and SD)
DK	DKED	19.41(2.58)	25.79(5.74)	6.08(0.87)	6.04(1.06)
	DKJG	16.56(4.37)	27.09(6.01)	5.89(0.82)	2.63(0.90)
	DKMB	5.06(1.92)	9.10(2.80)	5.76(0.00)	3.64(1.13)
SG	SGJL	16.70(14.11)	5.22(2.38)	1.37(0.59)	4.36(0.93)
	SGJD	21.61(5.41)	14.51(4.65)	7.13(3.92)	2.00(0.71)
	SGLK	17.71(6.50)	23.81(6.33)	8.85(1.24)	5.43(1.33)
SA	SABD	6.41(3.23)	12.41(3.27)	1.85(0.03)	4.07(1.31)
	SAHS	7.76(1.06)	14.86(4.30)	2.02(0.22)	7.27(2.52)
	SAKT	8.19(0.99)	10.00(3.55)	3.75(0.70)	3.71(2.15)
BD	BDDT	10.78(2.13)	20.49(7.89)	2.25(0.55)	7.44(2.04)
	BDMG	19.23(2.65)	22.35(8.53)	6.88(2.16)	12.72(3.28)
	BDNW	11.91(1.63)	25.50(2.96)	3.00(0.43)	4.08(1.48)

Values are given as mean at each farm with SD in parentheses.

5.3.10.3 Rain Use Efficiency under manure experiment

RUE is significantly higher in the manured crop fields than in the unmanured crop fields ($P \leq 0.05$). The RUE of maize grain yields was 3.69 and 2.25 kg/ha/mm, in the manured and unmanured fields, respectively. Similarly, the RUE of bean grain yields was 2.75 and 1.72 kg/ha/mm, in the manured and unmanured fields, respectively (Table 5-17). The RUE was higher in the manured fields, because manure increases crop's grains and crop's non-food biomass, making the rainfall more productive.

Table 5-17: RUE for manured and unmanured crop fields (n=12)

Maize production			Beans production		
Manure treatments	Maize grains RUE (kg/ha/mm)	Maize total aboveground biomass RUE (kg/ha/mm)	Manure treatments	Bean grains RUE (kg/ha/mm)	Beans total aboveground biomass RUE (kg/ha/mm)
	Means and SE			Means and SE	
200 kg N/ha	3.69(0.53)a	20.44(1.49)a	100 kg N/ha	2.75(0.18)a	6.46(0.58)a
0 kg N/ha	2.25(0.30)b	13.32(1.27)b	0 kg N/ha	1.72(0.14)b	4.21(0.44)b

Means in each column that do not share a letter are significantly different at $P \leq 0.05$ by Tukey's HSD test. Values are given as mean for each treatment with SE in parentheses.

5.4 Discussion

Chemical and physical characteristics of soils: The chemical characteristics of soils were comparable among the locations of study (Table 5-3). Based on the nutrient threshold limits in Kenya, it is only total nitrogen which is deficient in the soils during the period of study. Total soil nitrogen of 0.20% is the minimum threshold limit for Marsabit agricultural area (Muya, Gitau et al. 2010, Berazneva, McBride et al. 2016). Thus, total nitrogen is inadequate in all the farms studied. Nitrogen is therefore, the most limiting nutrient in Marsabit-central farms. The soil P and K in the maize and bean fields were not deficient at the time of study. Nitrogen limitations need to be addressed to sustain food production in Marsabit-central. Sustainable use of manure for meeting the demand of soil nitrogen is worth pursuing.

Also, the physical characteristics of soils were similar across the locations of study. The clay particles dominated the soil texture while increasing with the soil depth. The clay-dominated soil texture influences the water holding capacity and the soil moisture.

Soil moisture: Soil moisture is important for the continued existence of plants and animals. SG location had better soil moisture in both the seasons of 2016 and 2017. In the season of 2016, SG location received lower rainfall than DK but it had better soil moisture. This location is situated less than 1 km from Marsabit forest and it has better tree cover that reduces loss of soil moisture through evaporation. Also, the farms in SG location are lower with an average altitude of 1008 m asl while the farms in DK location are on higher side with an average altitude of 1267 m asl. The rainfall run-off from the higher areas of DK location has the potential to replenish the soil moisture of lower farms in SG location. This finding is in line with other study which reported low soil moisture in up-fields with shallow soils and found better soil moisture in low lying mid-fields (Tromp-van Meerveld and McDonnell 2006).

Closely looking at soil moisture along the soil depths show that the soil moisture is higher at 1000 mm soil depth. 78% of maize roots are in the top 300 mm of soil (Dwyer, Stewart et al. 1988). Additionally, the rooting system of a common bean dwells between 70 mm to 400 mm from emergence to flowering stages. Similarly, the lateral root system of a common bean concentrates around 300 mm (Beebe, Rao et al. 2013). The crops available soil moisture in 100 mm to 300 mm soil depths is less than the soil moisture in deeper 400 mm to 1000 mm depths. The increase of soil moisture with soil depth is partly due to increasing clay with soil depth as clay soils stores more moisture. Also, the plant available soil moisture in the sub-surface is likely lost through evaporation. The potential annual evaporation in the study area is 1550-2300 mm (Sombroek et al 1982). Consistently, the increase of soil moisture with soil depth has also been shown in other part of Kenya (Bohme, Becker et al. 2013), and also in other part of the world (Melliger and Niemann 2010).

Soil moisture pattern and planting time: The rainfall in Marsabit-central influences the dynamics of soil moisture. The positive relationship between soil moisture and seasonal precipitation is also reported in central Kenya (Bohme, Becker et al. 2013). The rainfall pattern and soil moisture have an implications on the planting time by crop farmers. The farmers in the study area plants their staple crops (maize and beans) in the month of April to early month of May. The farmers have custom of "see enough rain and plant". This tendency is caused by fear of drought occurrence and crop failure. However, a higher proportion of rain is usually received in the month of April, before most farmers in the study area plants their crops. Similarly, soil moisture increases in the month of April up to mid-May (during higher rainy days) and start reducing after mid-May. In order for the farmers to make optimal use of soil moisture, planting crops in the month of March is more appropriate.

Crop grain yields and non-food biomass from farmer's fields: The inconsistency of rainfall during the years of study and nitrogen limitations resulted in differences in both crop grain yields and total aboveground biomass (Tables 5-6, 5-7 and 5-8). The relationships between rainfall and grain yields or aboveground plant biomass has also been reported in other work (Afolabi, Omonijo et al. 2009). While the media and government bodies put blames of low yields entirely on variable rainfall pattern, this study has shown that nitrogen limitations also contribute to low crop yields in Marsabit-central. The average maize grain yields of 1.27 and 0.87 t/ha in the 2016 and 2017 seasons, respectively, is generally low. This finding is comparable with maize grain yields production of 0.48 – 2.10 t/ha reported in western part of Kenya. Consistent with this study, is also result of maize non-food biomass (stover) production shown to be 0.18 - 2.93 t/ha (Castellanos-Navarrete, et al 2015). Similarly, this work showed average bean grain yields of 0.80 t/ha and 0.57 t/ha in the seasons of 2016 and 2017, respectively. This is comparable with the bean grain yields ranging from 0.32 - 0.63 t/ha reported in other part of Kenya (Ojiem, Franke et al. 2014).

Nitrogen balance: In Marsabit-central, more nitrogen is harvested from the crop fields and less quantity of nitrogen is supplied to the crop fields. This study has shown that the biggest contributor to the negative nitrogen balance is the non-food biomass (stover) of maize. The negative nitrogen balance is further exacerbated by non-use of mineral fertilizer coupled with minimal use of manure. Consistent with the findings of this study, the nitrogen balance of -112 kg/ha has been reported in Kissii district of Kenya (Smaling, Stoorvogel et al. 1993), and negative nitrogen balance has been reported in various parts of Kenya (Sheldrick, Syers et al. 2002) (Gachimbi, van Keulen et al. 2005). Similarly, previous studies across SSA have reported negative nitrogen balances in crop fields (Smaling, Stoorvogel et al. 1993, de Jager, Kariuku et al. 1998, Shepherd and Soule 1998, Van den Bosch, Gitari et al. 1998, Esilaba, Nyende et al. 2005, Gachimbi, van Keulen et al. 2005). The prevailing negative nitrogen balance in Marsabit-central and in SSA is due to low nutrient input. The negative nitrogen balance and low availability of total nitrogen concentrations in the soils indicate unsustainable production system. The continuous removal of already deficient nitrogen is detriment to the food security in Marsabit-central. A viable measure to address this condition is required. The optimal use of manure resource to maintain sustainable production systems is a feasible option.

Crop production under manure fertilizer: In this work, manure increased maize and beans grain yields and non-food crops biomass, despite the below-average rainfall received in 2017 season. The manure in this region can lessen food shortage and also can improve nitrogen balance in the crop fields. Similarly, the increase of crop yields with manure application has been reported in other study (Fofana, Zida et al. 2012). Use of mineral fertilizer may have less economic returns than manure fertilization, in addition to potential detriments to the environment. Although, the government has been advocating increased use of mineral fertilizer, this has not been fully adopted by farmers, partly because of financial reason (Misiko, Tittonell et al. 2011). Manure is the most adoptable and affordable source of fertilizer for the resource-constrained farmers in arid and semi-arid lands of Kenya. Therefore, manure fertilizer remains the better option for improving food production in Marsabit-central and other similar parts of Kenya.

Manure production: The 1.71 kg of dry manure produced by TLU per day in the study area is comparable to the finding of ILRI which reported production of 1.80 kg of dry manure per day per TLU. This is equivalent to 660 kg of DM manure per year (Achard and Banoin 2003). In another study, DM manure of 2.7 kg per day per TLU is estimated (Graefe, Schlecht et al. 2008). Similarly, DM faecal excretion between 1.1 to 2.7 kg per day per TLU has been reported in various African countries (Ayantunde, Fernandez-Rivera et al. 2002) (Khombe and Dube 1992). The manure produced by livestock in Marsabit-central can be efficiently used to curb the nitrogen limitations and reverse the negative nitrogen balance. A farmer in Marsabit-central owning 20 TLUs, can produce 34.2 kg DM manure per day. This is equivalent to 12,483 kg DM manure per year. This farmer produces 250 kg of total nitrogen per year. Previous work in Kenya reported nitrogen production from manure ranging from 4 – 358 kg per ha per season (Castellanos-Navarrete, Tittonell et al. 2015). However, the amount of nitrogen supplied by livestock manure depends on the number of TLUs and the collectable manure.

This work has also shown that manure reduces in quality with increase in age. This accords with other study which reported that length of manure storage is vital than the methods of storage (Tittonell, Rufino et al. 2010). The collection and management of manure need to be optimized to realize the full fertilizer value of manure produced in this region. Cattle and crops (maize and beans) production are two sub-systems depending on each other. While cattle provides manure for soil fertilization, maize and beans non-food biomass provides cattle feed during drought and dry periods. In this area, the management of cattle and crops (maize and beans) need to be fully harmonized, and it is necessary to use manure in the first 4 months of its life time.

Rain Use Efficiency: The variability of rainfall in Marsabit calls for efficient utilization of each drop of rain. Previous work has estimated that only about 10-15% of rain that falls to the ground is made into beneficial use of food production. Rain is lost through various ways including surface run-off, evaporation and deep percolation (Stroosnijder 2009) (Rockstrom, Barron et al. 2002). Loss through evaporation is possible in the study area due to relatively high temperature, average daily temperature being 25 ^{o}C (Average of maximum temperature: 1974-2013). Similarly, loss through surface run-off is probable, considering dropping gradient from crop fields (mountain) to grazing lands (lowlands). The loss of rain can also be aggravated by downpour of rainfall in one month period and there being minimal effort of rainfall harvesting for food production. These losses have likely been making physical blue water in Marsabit-central unproductive.

There is low global water use efficiency in agricultural production, with only about 45% of agricultural water put to productive use (Hamdy, Ragab et al. 2003). Therefore, understanding portion of rainwater used productively is necessary for dominant rainfed systems in arid and semi-arid areas. In arid and semi-arid lands of the world, RUE has been reported to be stable at 4 kg dry matter/ha/year/mm rainfall (Lehouerou 1984). However, the stable RUE reported cannot be the case as shown by this work and other previous studies.

The findings of this study compares well with the work of Getnet, Van Ittersum et al. (2016), which reported water use efficiency ranging from 2.7 to 4.3 kg/ha/mm for maize grain yields in Central Ethiopia. The work in Zambia also showed maize grain RUE ranging from 2.5 to 4.6 kg/ha/mm which is consistent with our findings on RUE for maize grain yields (Sileshi, Akinnifesi et al. 2011). In Machakos County of Kenya, water use efficiency of maize grains ranged from 2.2 to 3.1 kg/ha/mm, and is argued to be typical of rainfed agriculture in SSA (Rockstrom, Barron et al. 2002). Water use efficiency of *morales* bean grains ranging from 1.4 to 4.5 kg/ha/mm under different moisture conditions has also been shown (Builes, Porch et al. 2011). The RUE of maize and beans reported in the literature is comparable to the RUE findings for grain yields only. The earlier studies largely overlooked on revealing RUE for total aboveground crop biomass.

Moreover, if total aboveground biomass is considered, the average RUE escalates. For example, in the season of 2016, the maximum RUE for total aboveground biomass was 21.61 and 8.85 kg/ha/mm for maize and beans, respectively (Figure 5-16). The RUE for total aboveground biomass accounts for both crop grains and non-food crop biomass. The non-food crop biomass is an important livestock feed. This RUE defines total amount of rain used for beneficial transpiration. While most of the studies dwelt on RUE for crop grain yields only, it is worthwhile to consider RUE for total aboveground crop biomass.

The RUE for crop fields were also higher in the 2017 season than in the season of 2016, and the latter season had better rainfall. For example, the average RUE of total maize aboveground biomass was 17.6 and 13.4 kg/ha/mm, for the seasons of 2017 and 2016, respectively. Consistently, better RUE was reported with seasonal rainfall of 425 mm than the seasonal rainfall of 824 mm (Fofana, Breman et al. 2004, Kihara, Bationo et al. 2011). There were contradicting reports in arid and semi-arid areas, on whether, RUE is better with low rainfall or is better with higher rainfall (Wessels, Prince et al. 2007). Nevertheless, the findings of this study is in line with body of knowledge asserting that RUE is higher when rainfall is smaller.

It has been reported that seasonal rainfall of 260 mm to 310 mm is required for dry land farming and also a total rainfall amount of about 508 mm to be sufficient for maize production (Forouzani and Karami 2011). With the use of water management practices, crop production with seasonal rainfall of 89.9 mm – 138.3 mm has been reported in Eastern, semi-arid Kenya (Wang, Mo et al. 2016). In Marsabit, the mean long season rainfall since the year 1960 is 361.0 mm. Similarly, in the 2016 long rain season, an average of 487.0 mm and 568.0 mm of rainfall was received by SG and DK locations, respectively. Also, a rainfall amount of 333.7 mm, 267.3 mm and 156.2 mm was received in the year 2017 long rain season by SG, BD and DK locations, respectively. Contrary to blames put on meteorological drought for low grain and biomass yields, the rainfall in Marsabit-central can be efficiently used to produce human food (maize and bean grains) and cattle feed (maize and beans non-food biomass and pasture), in ideal crop-livestock systems. The low RUE in the study area presents opportunity to make better use of available rainfall. This is also alluded by other study which has reported that, average rain use efficiency of up to 20 kg/ha/mm of rain can be attained in Kenya (Tittonell, Leffelaar et al. 2006). Similarly, other work has asserted synergistic benefits of rainwater harvesting practices and use of organic fertilizer in arid and semi-arid agriculture of Africa (Zougmore, Mando et al. 2004). This is in line with the findings of this study which demonstrated that use of manure can increase RUE. Agricultural interventions in Marsabit central sub-county need to focus on technologies that put more rain and manure into beneficial use.

Sustainability indicators: Nitrogen balance gives indication about whether nitrogen input is more, equal to or less than nitrogen output. Nitrogen balance do not portray limitations or availability of a nitrogen in the production systems. It is therefore imperative to use nitrogen balance simultaneously with the status of soil nitrogen to make land-use decisions. Nitrogen concentrations in soils and the nitrogen balance are complementary indicators in Marsabit-central food production systems. This work showed deficient nitrogen in soils as well as negative nitrogen balance in the farms. The limitations of nitrogen in this system is more pressing than any other factors of production. This finding calls for interventions geared at addressing nitrogen limitations. This can guide the decisions of Marsabit county government and other development organizations. The concentrations of nitrogen in soils and nitrogen balance are reliable sustainability indicators in Marsabit-central farms. The use of nitrogen balance with the status of soil fertility as a sustainability indicators have also been reported in other work (Sassenrath, Schneider et al. 2013) (Van den Bosch, Gitari et al. 1998). Regular monitoring of soil nitrogen and nitrogen balance gives the Marsabit-central crop farmers opportunity to maintain sustainable production systems. The total nitrogen concentrations in the agricultural soils in combination with the nitrogen balance of the crop fields are recommended as a yardstick for sustainable food production systems in Marsabit-central.

5.5 Conclusion

The rainfall has influences on soil moisture and thereby soil moisture varies significantly between the locations and along 100 mm to 1000 mm soil depths. The downpour of rain in the month of April, calls for timely planting. In order to make productive use of rain and soil moisture in marsabit-central, planting crops in the month of March is recommended. Furthermore, nitrogen is the most limiting nutrient in Marsabit-central crop farms. Thus, the variable rainfall and limited nitrogen have resulted in low crop yields.

The increasing demand for more food to feed growing human population in Marsabit-central and similar regions in Africa can be attained through productive use of rainfall and manure resources. Use of manure for soil fertilization can increase grain yields and non-food crop biomass production, making rain more beneficial to humans and livestock. Rain-manure synergy is a plausible strategy to improve crop production in Marsabit-central and other similar environment.

RUE is an important indicator in water-scarce and variable environment, to understand portion of rain used for food and biomass production. In addition, RUE for total aboveground biomass is more informing than RUE for crop grains that populated the scientific literature. The former captures total rain used for productive purpose. Hence, RUE for total aboveground crop biomass is recommended in a similar crop-livestock environment.

Sustainability indicator makes it possible for continuous monitoring of a production systems. Soil nitrogen and nitrogen balance of the crop fields are recommended for sustainability indicators in Marsabit-central food production systems.

Chapter 6 : Scenario analysis

6.1 Introduction

Scenario analysis involves pursuing various options and providing alternative solutions to the existing challenges. Scenario analysis is carried out under varied assumptions. The analysis provides opportunity to explore different mechanisms for attaining desired outcomes (Bood and Postma 1997). The solution to limiting soil nutrient and low food production in Marsabit-central farms lies in diverse scenarios.

The depletion of nitrogen in the crop farms of Marsabit-central can be addressed through two main ways: One is through cereal-legume rotations to fix nitrogen, second is the use of livestock manure. The livestock-mediated manure is the integral part of crop-livestock systems across SSA.

In SSA, the importance of manure in maintaining soil fertility has been widely recognized (Brouwer and Powell 1998, Rufino, Tittonell et al. 2007, Diogo, Schlecht et al. 2013). In addition to addressing nutrient limitations, manure also improves soil water holding capacity, cation exchange capacity, improves soil pH and soil structure (Williams 1999). Manure is the most affordable input that can sustain food production among resource-constrained farmers. Extensive grazing lands in ASAL areas of SSA produces livestock-mediated manure.

Marsabit-central crop farms are surrounded by extensive grazing lands. These grazing lands are used commonly by the community. The main use is for cattle grazing. Cattle are grazed both in upper local fields and in distant lower grazing lands.

The crop-livestock farmers of Marsabit-central have an opportunity to utilize the livestock manure for fertilizing their crop fields. Local grazing of livestock in upper home fields enable close collection of manure for field's fertilization. Also, the transportation of manure from distant grazing lands may be a feasible option provided that the transportation constraint can be addressed.

Collection of livestock manure from the distant grazing lands require a consideration of the following factors: Firstly, the transportation cost, and secondly, the quantity of collectable manure versus distance of moving into the grazing lands. Collection of manure from a long distant grazing land raises the cost of food production but it also increases the quantity of collectable manure to fertilize maize and beans fields.

Maize and beans are currently the dominant crops grown by the farmers of Marsabit-central Sub-County. The nitrogen limitations can also be addressed through organized rotation of maize and beans. The dual opportunities of using livestock manure and systematized maize-bean rotations can reverse the current trend of nutrients mining.

This chapter addresses objective 4: *To explore various options and recommend sustainable food production alternatives*

The chapter seeks to:

i. Identify the spatial and temporal availability of manure. Therefore, the quantity of the manure that crop farmers can collect from local grazing as well as quantity of manure collectable from the distant grazing lands is reported. Also, the seasonality of collectable manure is shown.
ii. Describe the NPK production from collectable manure.
iii. Show various alternatives of maize-beans production.
iv. Present the NPK balance under manure fertilization.
v. Reveal the hectares of grazing lands required to fertilize crop-field.

6.2 Description of production scenarios in Marsabit-central sub-county

The scenarios involve crops and livestock sub-systems. The crops sub-system involves maize and bean crops. The scenarios consider that maize and beans are either solely planted or can also be pursued through the rotation systems. Maize-beans rotation involves the following: a) a two-year rotation system, in this case 50% land is under maize production and 50% land is under beans production, b) a three-year rotation system, with 66% land under maize production and 34% land under beans production , c) a four-year rotation system, with 75% land under maize production and 25% land under beans production.

The livestock sub-system involves cattle grazing in upper local fields and also grazing in distant lower grazing lands. Long rain season involves cattle utilizing forage biomass from local and low-altitude grazing lands close to the crop fields, whereas short rain season involves utilization of forages from only the local fields. Long and short rain seasons affect the accessibility of manure.

Manure resource links the crops and livestock sub-systems. Manure is currently the only input used for fertilization of Marsabit-central crop fields. Cattle grazing in upper local fields and in distant lower grazing lands provide manure for fertilization of crop fields (Figure 6-1).

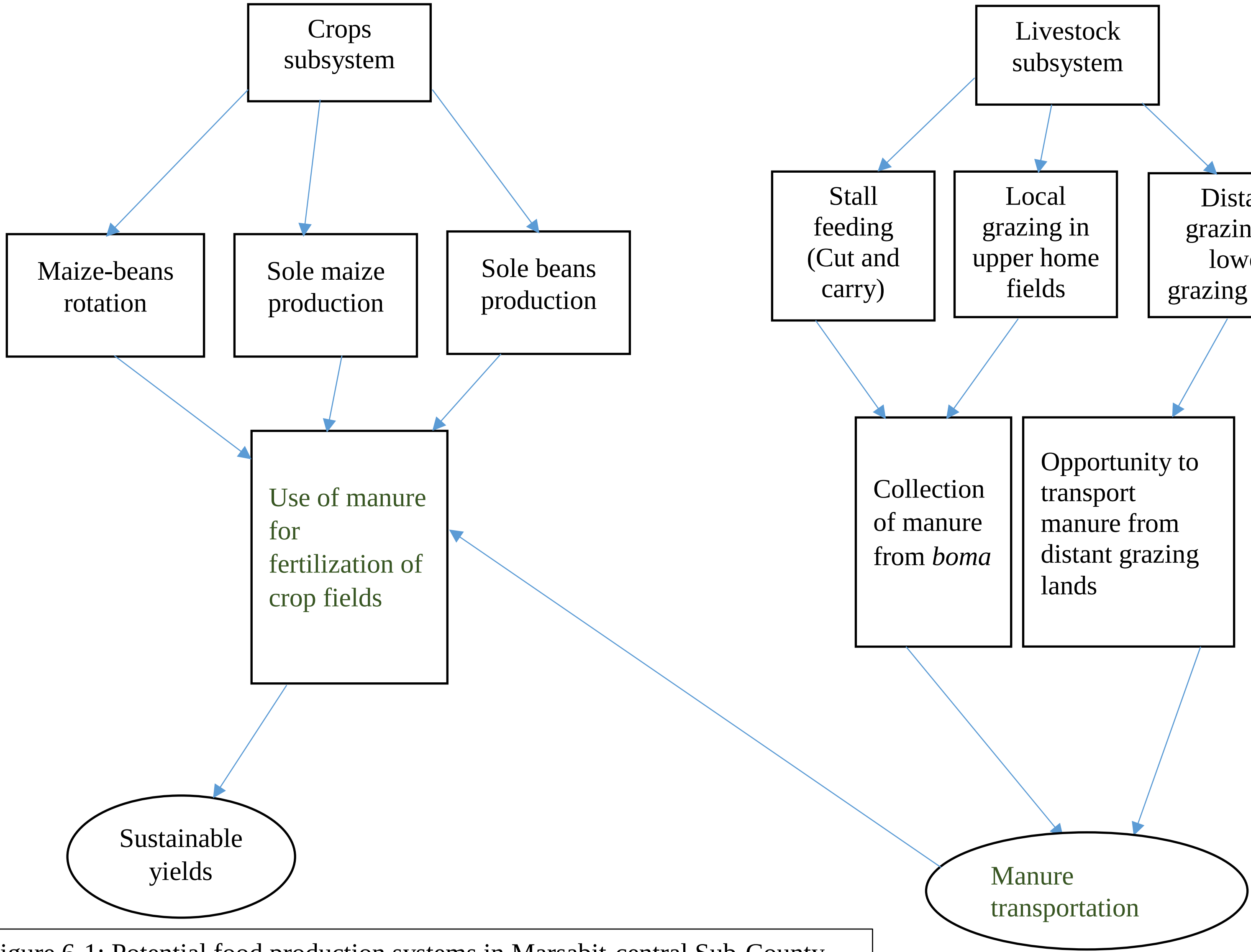


Figure 6-1: Potential food production systems in Marsabit-central Sub-County

6.3 Key assumptions behind the scenario analysis

1. Palatability of forage biomass is higher in the upper home fields, and reduces as it move further into the distant lower grazing lands. This is confirmed during field-work phase of the study and also from remotely-sensed work.
2. High, medium and low levels forage palatability represent 75-59%, 65-51% and 55-43%, respectively. Palatable forage biomass is the forages available for livestock to feed on.
3. Long rain season produces forage biomass that can feed TLUs for 200 days while short rain season for 165 days. The forage biomass produced in long and short rain seasons feed TLUs for one year (365 days). The population of TLUs determine the quantity of manure production.
4. In the long rain season, the maximum distance of manure collection is within a radius of 22 km, with a semi-circle grazing area of 75,988 ha. The semi-circle grazing area is selected because farmers in Marsabit-central grazes livestock mainly in a single direction from Marsabit town down into the lower grazing lands. The unutilized remaining semi-circle area is largely covered by protected natural forest.
5. In this analysis, distant grazing lands means a common low-lying grazing lands with a maximum distance of 22 km from the upper home fields.
6. In the short rain season, the maximum distance of manure collection is within a radius of 7 km, with a semi-circle grazing area of 7,693 ha.
7. Local grazing means utilizing of upper grazing fields with a maximum distance of 7 km from home fields. It involves either, cattle grazing during day and coming to spend in home *boma* (i.e. enclosure) at night or cut and carry system, where farmers cut pasture and feed cattle in home-based *boma.*
8. The collectable manure involves 50%, 40% and 30% of the produced manure. The upper limit of 50% represents a scenario where livestock are kept for 12 hours per day in a "*boma*" and manure in *boma* are all collected. Lower values allow for conditions where not all livestock keepers collect manure for fertilization of crop fields.
9. In median long rain season, maize yields range from 1.0 - 4.0 t/ha and bean yields range from 0.5 - 1.5 t/ha.
10. In median short rain season, maize yields range from 0.5 - 1.5 t/ha and bean yields range from 0.4 - 1.0 t/ha.

6.4 Justification for potential crop yield values and the rotations system used

This study identified maize grain yield values ranging from 0.45 – 3.35 t/ha, and from 0.14 - 1.46 t/ha, in the 2016 and 2017 long rain seasons, respectively.

Furthermore, in the long season of 2016, bean grain yields ranged from 0.11 – 1.46 t/ha, and in 2017, it ranged from 0.42 – 0.75 t/ha (Tables 5-6 and 5-7). The crops yield values are under the farmer's practices.

Additionally, according to FAO data of the years 2005 - 2016, the average yield value of maize grains in Kenya is 1.62 t/ha and the average bean grain yields is 0.54 t/ha (http://www.fao.org/faostat/en/#data/QC, accessed 10th May, 2018).

The rotations system may involve two-year, three-year and four-year rotations, with increasing maize intensity of 50% land maize and 50% land beans, 66% land maize and 34% land beans, and 75% land maize and 25% land beans, respectively. The increasing maize intensity is to conform to the current food production practices where Marsabit-central farmers allocate more land for maize production than beans production.

6.5 Methods used in the scenario analysis

6.5.1 Measurements used in the scenario analysis

The following measurements were used to run the model. The measurements were sourced during the fieldwork phase of this study and others from published literature (Table 6-1).

Table 6-1: Measurements used in the scenario analysis

Materials	Measurements	Sources
Manure (dry) production per day per TLU (kg)	1.71	Own work
Nitrogen concentrations in dry manure (%)	2.00	Own work
Rain Use Efficiency of forages (kg/ha/mm)	8.7	Average of own work and other studies (Prince, De Colstoun et al. 1998, Paruelo, Lauenroth et al. 1999, Bai, Wu et al. 2008, Ruppert, Holm et al. 2012)
TLU daily DM forage intake (kg)	6.25	(Cordova, Wallace et al. 1978, Smith and Pearson 2005)
Maize harvest index	0.27	Average of own work and other studies (Jensen, Bernhard et al. 2003, Muthuri, Ong et al. 2005, Tittonell, Vanlauwe et al. 2008, Wasonga, Sigunga et al. 2008).
Beans harvest index	0.41	Own work

6.5.2 Collection of manure from distant grazing: Long rain season

Forage production: The forage biomass used for this analysis was produced during rainfall with 50% probability of exceedance (Chapter 4, Figure 4-16). The forage biomass is accumulated from semi-circle area within 22 km radius and with a centre at 38.00 Easting, and 2.30 Northing.

The home fields close to Marsabit town are at high altitude and represent good grazing lands. However, the more distant grazing lands are at lower altitude and represent poor grazing lands (Chapter 3, Figure 3-2). The forages in upper grazing lands have high palatability than the forages in lower grazing lands. Palatability of forage biomass reduces from high to low, as it moves into the more distant grazing lands.

Number of TLUs fed by the forages produced: One cattle consumes about 2.5% of its live weight per day (Cordova, Wallace et al. 1978, Smith and Pearson 2005). One TLU (matured cattle) weighs 250 kg. Therefore, one TLU consumes 6.25 kg dry forage matter per day. The long rain season produces forage biomass that can feed TLUs for 200 days. Number of TLUs supported by forage biomass was computed as follows:

$$\text{Number of TLUs fed/season} = \frac{\text{Cumulative palatable forage biomass (kg)}}{6.25\ \text{kg} * \ 200\ \text{days}}$$

Quantification of manure produced: One TLU produces 1.71 kg dry manure per day. The manure production is calculated based on this information.

$$\text{Manure produced (kg/season)} = \text{Number of TLUs} * \ 1.71\ \text{kg} * \ 200\ \text{days}$$

Not all farmers can be affording to collect manure from distant grazing lands. Similarly, those farmers collecting manure are not likely to collect 100% of manure produced. Therefore, collectable manure is assumed to be 50%, 40% or 30% of the produced manure.

6.5.3 Quantification of nitrogen produced from manure

Cattle manure contains about 2% total nitrogen (Chapter 5, Table 5-10). The nitrogen produced by the livestock manure is based on this percentage.

$$\text{Nitrogen production (kg/season)} = \frac{2}{100} * \ \text{collectable manure (kg/season)}$$

6.5.4 Quantification of crop grains and non-food crop biomass

Harvest index is the ratio of grain yield to the total aboveground biomass. In Kenya and other similar environment, previous studies have reported maize harvest index ranging from 0.11 to 0.40 (Jensen, Bernhard et al. 2003, Muthuri, Ong et al. 2005, Tittonell, Vanlauwe et al. 2008, Wasonga, Sigunga et al. 2008). This work showed maize harvest index of up to 0.35, with an average of 0.18. However, harvest index is subject to variable environment, variety of maize crop and the management of crop fields. For the purpose of this analysis, average maize harvest index was computed from this work and previous studies. This resulted in maize harvest index of 0.27. This harvest index was used to calculate non-food maize biomass under different maize grain yields production.

Additionally, this work also revealed average bean harvest index of 0.41. Other studies have also reported harvest index of common beans ranging from 0.38 to 0.55 (Pilbeam 1996, Cernay, Pelzer et al. 2016, Sennhenn, Njarui et al. 2017). Therefore, bean harvest index of 0.41 was used to compute production of non-food bean biomass under various bean grain yields production.

6.5.5 Scenarios of crops production in Marsabit-central

This scenario analysis considered 2 classes of yield production. These include: a) Long rain season scenario, b) Short rain season scenario.

Long rain season scenario

The long rain season scenario has better yields. This scenario can occur under the long season rainfall with 50% probability of exceedance. It involves utilization of manure from local and distant grazing lands.

1. **Long rain season scenario 1**: This is a sole maize production scenario. This involves 3 types of maize grain yields and non-food maize biomass production: a) production of 1.0 t/ha maize grain yield, having 3.0 t/ha maize non-food biomass, b) production of 2.0 t/ha maize grain yield, having 5.0 t/ha maize non-food biomass, c) production of 4.0 t/ha maize grain yield, having 11.0 t/ha maize non-food biomass (Table 6-2).

2. **Long rain season scenario 2**: This scenario involves sole beans production. This includes: a) production of 0.5 t/ha beans grain yield, having non-food beans biomass of 0.72 t/ha, b) production of 1.0 t/ha beans grain yield, having non-food beans biomass of 1.44 t/ha, c) production of 1.5 t/ha beans grain yield, having non-food beans biomass of 2.16 t/ha (Table 6-2).

3. **Long rain season scenario 3:** This is maize-bean rotations scenario: a) 50% of cropland under maize production and 50% of cropland under beans production, b) 66% of cropland under maize production and 34% of cropland under beans production, c) 75% of cropland under maize production and 25% of cropland under beans production. These represent respectively, two-year, three-year and four-year rotations with increasing intensity of maize production (Table 6-2).

Table 6-2: Crops production under long rain season scenario

Scenarios	Low yield	Medium yield	High yield
Maize grain yield (t/ha)	1.00	2.00	4.00
Maize non-food biomass (t/ha)	3.00	5.00	11.00
Beans grain yield (t/ha)	0.50	1.00	1.50
Beans non-food biomass (t/ha)	0.72	1.44	2.16

Quantification of nitrogen uptake in long rain season scenario

Nitrogen uptake (kg/ha) = % nitrogen concentrations (Table 5-2) * 10 * grain yield or non-food crop biomass (t/ha)

Meeting of the soil nitrogen demand based on the uptake of nitrogen by crop grains and non-food crop biomass fosters nitrogen-balanced food production systems (Table 6-3).

Table 6-3: Nitrogen uptake (kg/ha) of long rain season scenarios

Scenarios	Low yield	Medium yield	High yield
Sole maize fields	55.60	97.80	209.00
Sole bean fields	33.01	66.02	99.03
50% land maize and 50% land beans rotation	44.30	81.90	154.00
66% land maize and 34% land beans rotation	48.07	87.20	172.30
75% land maize and 25% land beans rotation	50.00	89.90	181.50

Determination of the area of crop fields fertilized from collection of distant manure

The quantity of nitrogen produced from livestock-mediated manure determines the area of crop fields that can be fertilized. This is under the condition of balanced nitrogen offtake and input.

Assuming collection of manure from up to within 22 km grazing distance, area of crop fields fertilized was calculated as follows:

$$\text{Area of crop fields (ha)} = \frac{\text{Total nitrogen produced from within 22 km distance manure (kg)}}{\text{Nitrogen uptake of crop (kg/ha)}}$$

6.5.6 Collection of manure from local grazing: Long rain season

This is a case where farmers utilize only the manure produced in the home fields. It involves collection of manure from the livestock that grazes in the semi-circular pasture area with a radius of 7 km. The livestock can go out to field for grazing in the day and comes into home *boma* at night or pasture can be cut and fed to livestock at a home-based *boma*. The manure collectable from local grazing of long rain season can be used to fertilize crop fields under long rain season scenario.

6.5.7 Collection of manure from local grazing: Short rain season

This involves collection of manure from within 7 km grazing distance in short rain season. The collectable manure in short rain season can fertilize crop fields under the short rain season yield scenario (Table 6-4 and Table 6-5). It is assumed that large number of livestock population are moving to long distance lowlands in search of pasture and water, and manure from them are not accessible.

Rainfall in the short season: The historical short season rainfall received in the months of October, November and December was used for analysis. The median of 47 years of historical short season rainfall was 262 mm at Marsabit town. Spatial variability of rainfall along 7 km distance was calculated based on the ratio of sites rainfall developed from 2016 study. The distance from starting point of the transect up to 7 km received 0.87 of rainfall received at Marsabit town.

Forage biomass produced in the short season: This involves production of forage biomass from half circular grazing area within the radius of 7 km. The rain use efficiency of 8.7 kg/ha/mm was used to calculate forage production (kg/ha). The palatability of forage biomass ranged from 75-70%. The forage biomass (kg) was calculated by multiplying the partitioned area (ha) by forage production (kg/ha). The cumulative forage biomass (kg) was identified by summing up forage biomass from within half-circular grazing area with a radius of 7 km grazing distance.

Number of TLUs fed by the forages: This involves the number of TLUs that can be fed for all the duration of short season (165 days). The TLUs supported by palatable cumulative forage biomass was revealed as follows:

$$\text{Number of TLUs/season} = \frac{\text{Cumulative palatable forage biomass (kg)}}{6.25\ \text{kg} * \ 165\ \text{days}}$$

Collectable manure in the short rain season: manure production was calculated as follows;

$$\text{Total manure produced (kg/season)} = \text{Number of TLUs/season} * 1.71 \text{ kg} * 165 \text{ days}$$

Collectable manure is assumed to be 50% of the produced manure. This is based on livestock being kept overnight (12 hours) in the home *boma* and all manure from *boma* being available for use in the crop fields.

Nitrogen produced by manure was computed as follows:

$$\text{Nitrogen production (kg/season)} = \frac{2}{100} * \text{ collectable manure (kg/season)}$$

Short rain season scenario

This scenario happens during the short rain season. The short rain season scenario is lower in yields production than the long rain season scenario. This is because the short rain season is less reliable and risk of crop failure is increased. It involves crop production using manure from local grazing. This scenario is recommendable in the season of manure limitation.

The short rain season scenario involves maize grain yields production ranging from 0.5 – 1.5 t/ha and bean grain yields production ranging from 0.4 – 1.0 t/ha. It also involves maize-bean rotations in various ratios. The ratios include 50% land maize and 50% land beans, 66% land maize and 34% land beans, and 75% land maize and 25% land beans. The nitrogen uptake of short rain season yields scenario is lower than the uptake in long rain season yields scenario (Table 6-4 and Table 6-5).

Table 6-4: Crops production under short rain season scenario

Scenarios	Low yield	Medium yield	High yield
Maize grain yield (t/ha)	0.50	1.00	1.50
Maize non-food biomass (t/ha)	1.40	3.00	4.00
Beans grain yield (t/ha)	0.40	0.70	1.00
Beans non-food biomass (t/ha)	0.60	1.00	1.44

Quantification of nitrogen uptake in short rain season scenario

Table 6-5: Nitrogen uptake (kg/ha) of short rain season scenarios

Scenarios	Low yield	Medium yield	High yield
Sole maize yields	26.46	55.60	76.70
Sole bean yields	26.84	46.07	66.02
50% land maize and 50% land beans rotation	26.65	50.84	71.36
66% land maize and 34% land beans rotation	26.59	52.42	73.14
75% land maize and 25% land beans rotation	26.56	53.22	74.03

Area of crop fields fertilized using collectable manure from local grazing

This is the area of crop fields fertilized under the short rain season scenario. The collectable manure is from upper home fields. Assuming collection of manure from half-circle grazing area from within radius of 7 km grazing distance, the area of crop fields fertilized under the condition of balanced nitrogen was identified as follows:

$$\text{Area of crop fields (ha)} = \frac{\text{Total nitrogen produced from within 7 km distance manure (kg)}}{\text{Nitrogen uptake of crop (kg/ha)}}$$

6.5.8 Calculation of nutrient balance

This is a partial nutrient balance and it was calculated by subtracting nutrient uptake by crop grains and non-food crop biomass from nutrient input by manure. The nutrient input was computed from the livestock manure applied to the fields. The N fixation by legume crop has not been considered. The nutrient uptake of maize and bean grains and non-food crop biomass was calculated from percentage nutrient concentrations. The nitrogen concentrations of manure, maize and bean grains and maize and beans non-food biomass were used to find the nitrogen flows (Table 5-2). The concentrations of P and K were also used to calculate nutrient flows (Table 6-6).

Table 6-6: P and K concentrations used to calculate nutrient flows

Materials	Nutrients	Nutrient concentrations (%)	Sources
Dry manure	Phosphorous (P)	0.40	Own work
Maize grains	Phosphorous (P)	0.22	(Van den Bosch, Gitari et al. 1998)
Maize non-food biomass	Phosphorous (P)	0.19	(Lesschen, Stoorvogel et al. 2004)
Bean grains	Phosphorous (P)	0.32	(Van den Bosch, Gitari et al. 1998, Lesschen, Stoorvogel et al. 2004)
Bean non-food biomass	Phosphorous (P)	0.36	(Van den Bosch, Gitari et al. 1998)
Dry manure	Potassium (K)	1.10	Own work
Maize grains	Potassium (K)	1.87	(Van den Bosch, Gitari et al. 1998)
Maize non-food biomass	Potassium (K)	2.05	(Van den Bosch, Gitari et al. 1998)
Bean grains	Potassium (K)	2.60	(Van den Bosch, Gitari et al. 1998)
Bean non-food biomass	Potassium (K)	2.81	(Van den Bosch, Gitari et al. 1998)

6.5.9 Ratio of grazing land to crop land

The area of grazing lands capable of providing manure for crop fields under balanced nitrogen fertilization, differs with the production scenarios. A semi-circle grazing distance with radius of 22 km has an area of 75,988 ha. The ratio of grazing land to crop land was computed as follows:

$$\text{Ratio of grazing land to cropland (ha)} = \frac{75{,}988\ \text{(ha)}}{\text{Area of crop fields (ha) fertilized by 22 km grazing distance}}$$

6.6: Results

6.6.1 Collection of manure from distant grazing lands in long rain season

6.6.1.1 Production of palatable forage biomass and number of TLUs supported

The palatability of forage biomass is higher in the upper home fields and less in the lower grazing lands. The upper home fields are in the land use class of good grazing lands while the lower grazing lands are in the class of poor grazing lands. The number of TLUs supported depends on the palatability of forage biomass (Figure 6-2). Within the half-circle grazing distance of 22 km radius, 50 - 69 * 10^3 TLUs can be fed by the forage biomass produced in median long rain season (Figure 6-3).

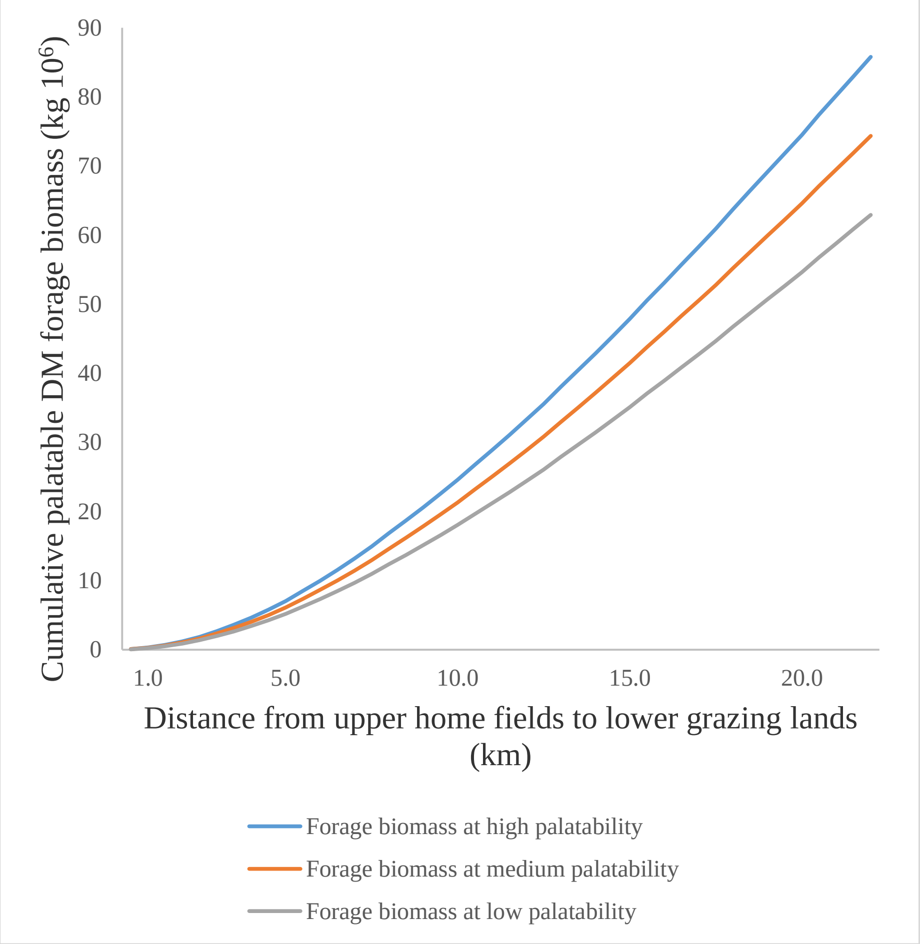


Figure 6-2: Cumulative palatable DM forage biomass (kg)

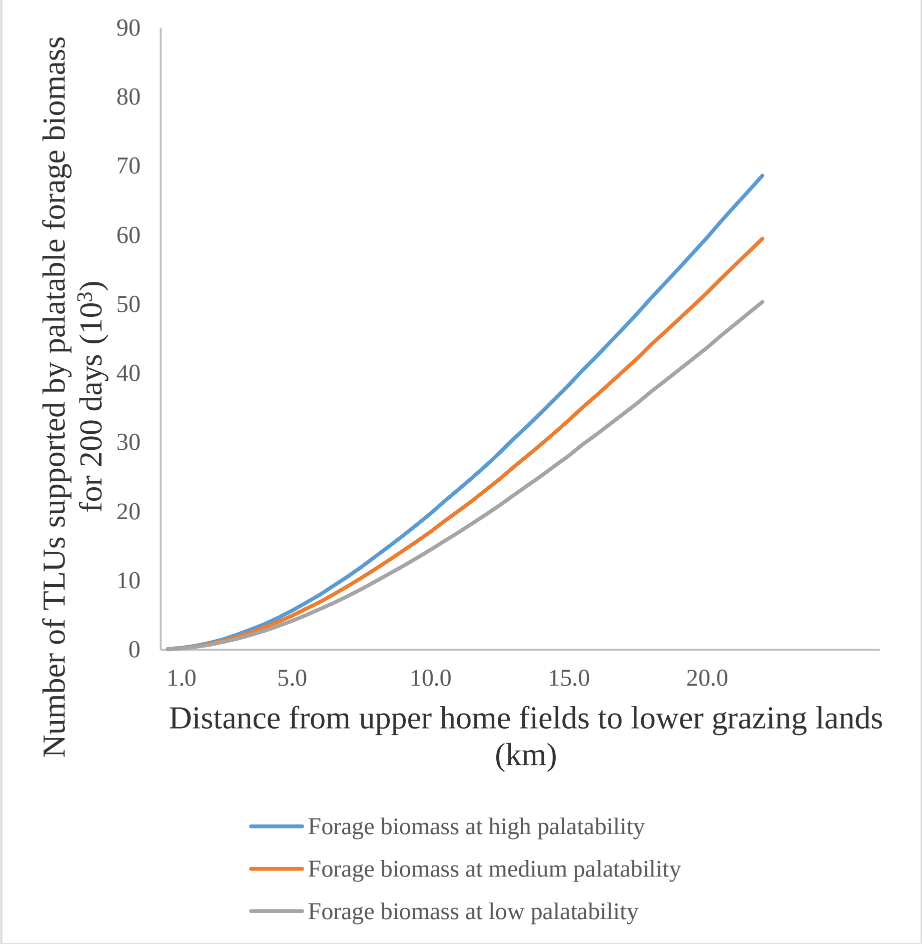


Figure 6-3: Number of TLUs supported by forage biomass

6.6.1.2 Manure production in the long rain season

All manure produced by the TLUs cannot be collectable. This is owing to possible lack of affording transportation cost and also possible unwillingness to collect manure by some livestock farmers. Also, some manure are dropped by livestock while feeding in the grazing fields and some manure are completely mixed with the soils while in the *boma*. Therefore, at its best 50% of manure is collectable and in bad case 30% of produced manure is considered collectable. Assuming use of grazing lands up to 22 km distance, total manure production is predicted to be in the range of 17 - 23 * 10^6 kg DM (Figure 6-4), and collectable manure that may be used in crop fields is predicted to be in the range of 5 - 12 * 10^6 kg DM (Figure 6-5).

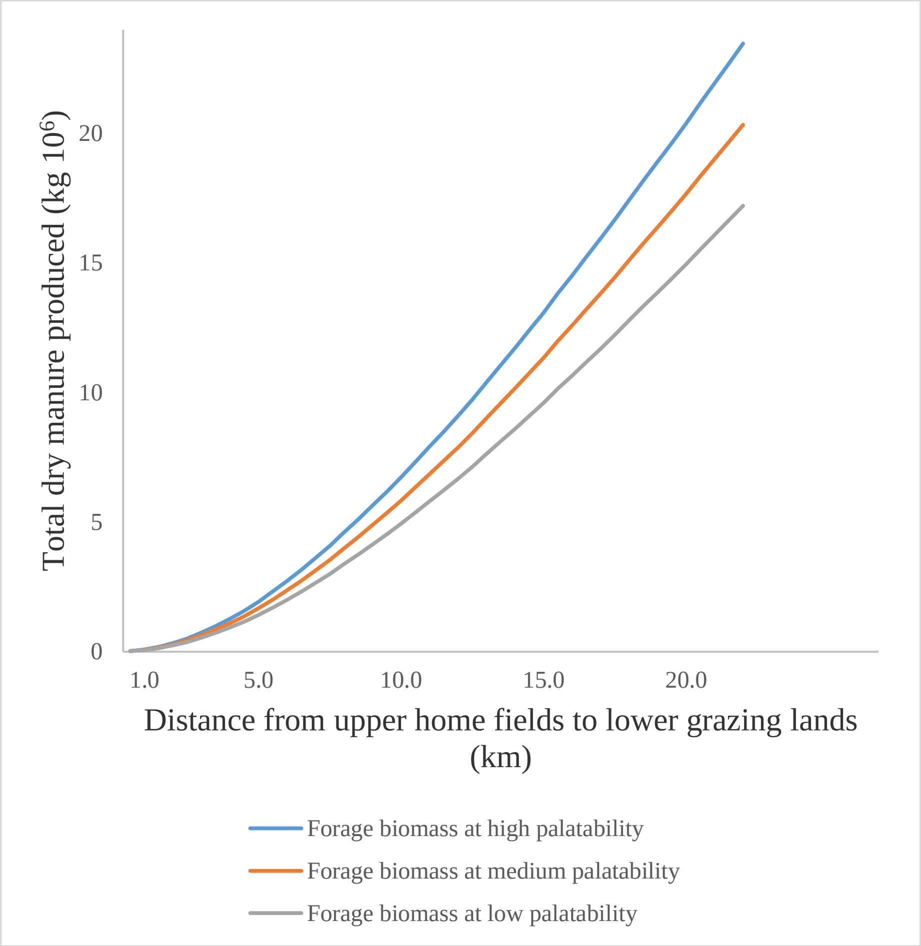
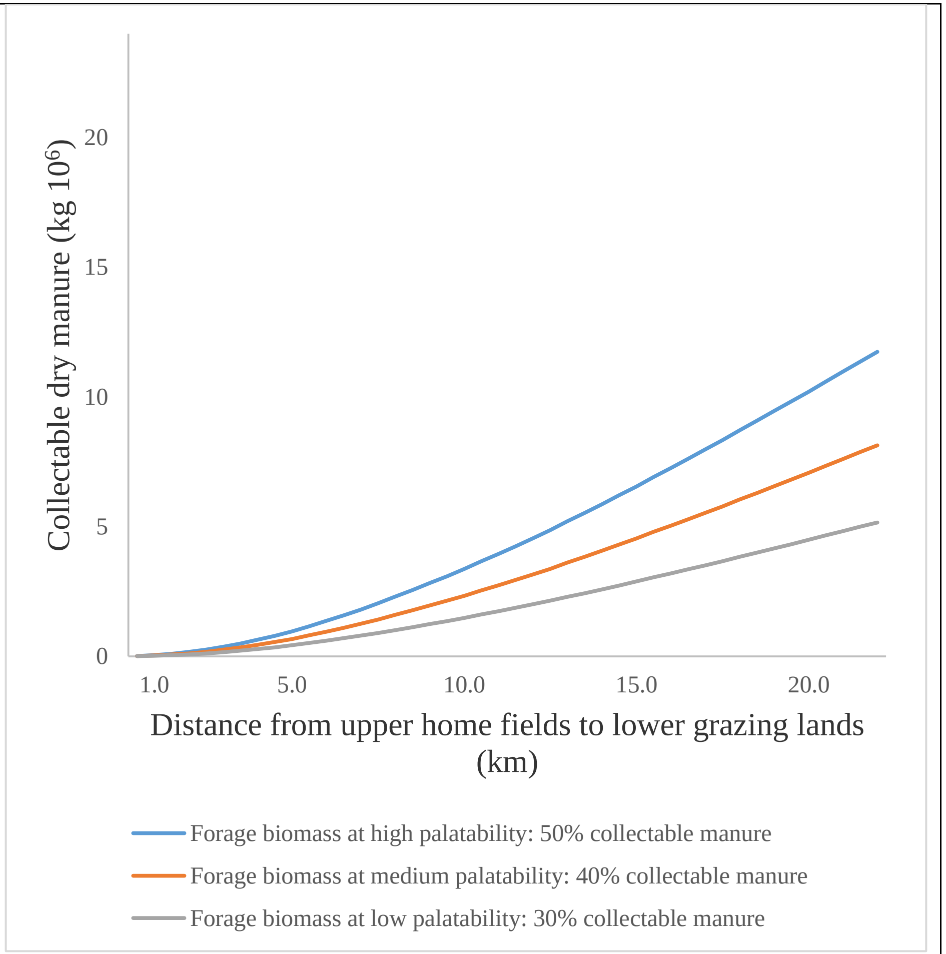
	

Figure 6-4: Total DM manure produced by TLUs (kg)	Figure 6-5: Collectable dry manure (kg)

6.6.1.3 Nitrogen production from collectable manure of distant grazing lands

Nitrogen is the main nutrient provided by the manure. The total nitrogen produced from within half circular grazing radius of 22 km ranged from 103 - 235 * 10^3 kg. The quantity of livestock-mediated nitrogen is higher with high palatability of forage biomass and also increases with the amount of manure collected for use (Figure 6-6).

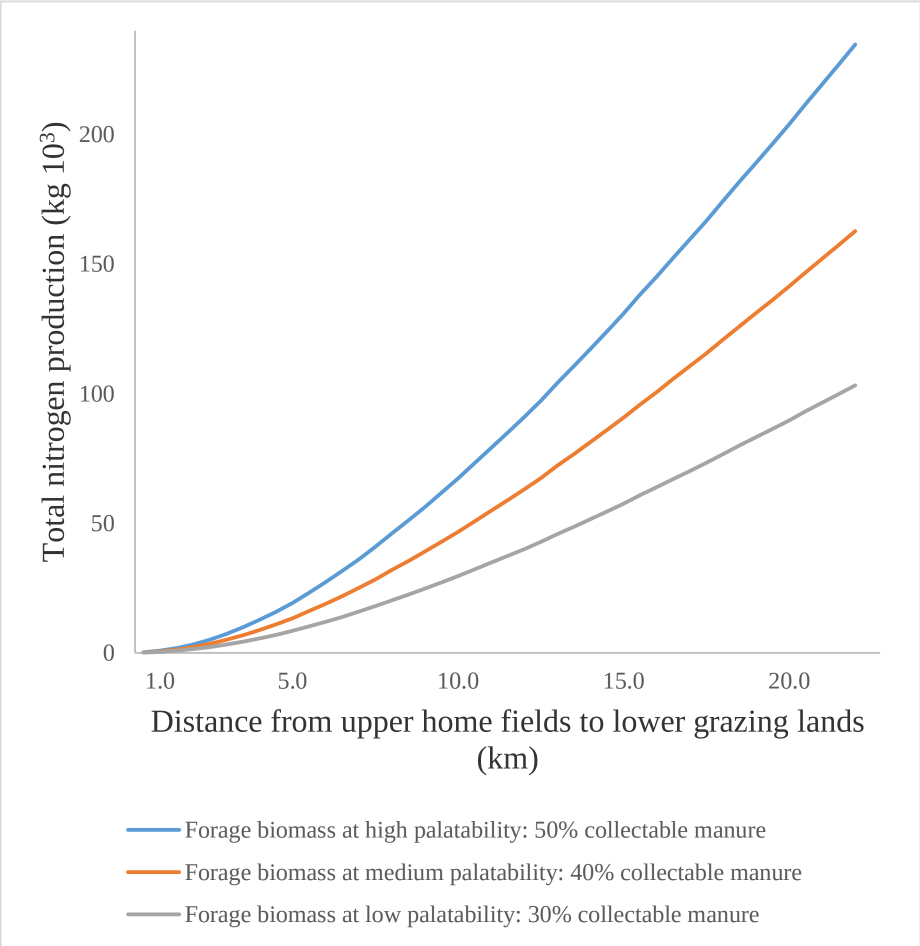


Figure 6-6: Nitrogen production from manure (kg)

6.6.1.4 Phosphorous and potassium production from collectable manure of distant grazing lands

The total phosphorous produced from within half circular grazing radius of 22 km ranged from 21 - 47 * 10^3 kg, and the total potassium produced from same area ranged from 57 - 129 * 10^3 kg (Figure 6-7 and Figure 6-8).

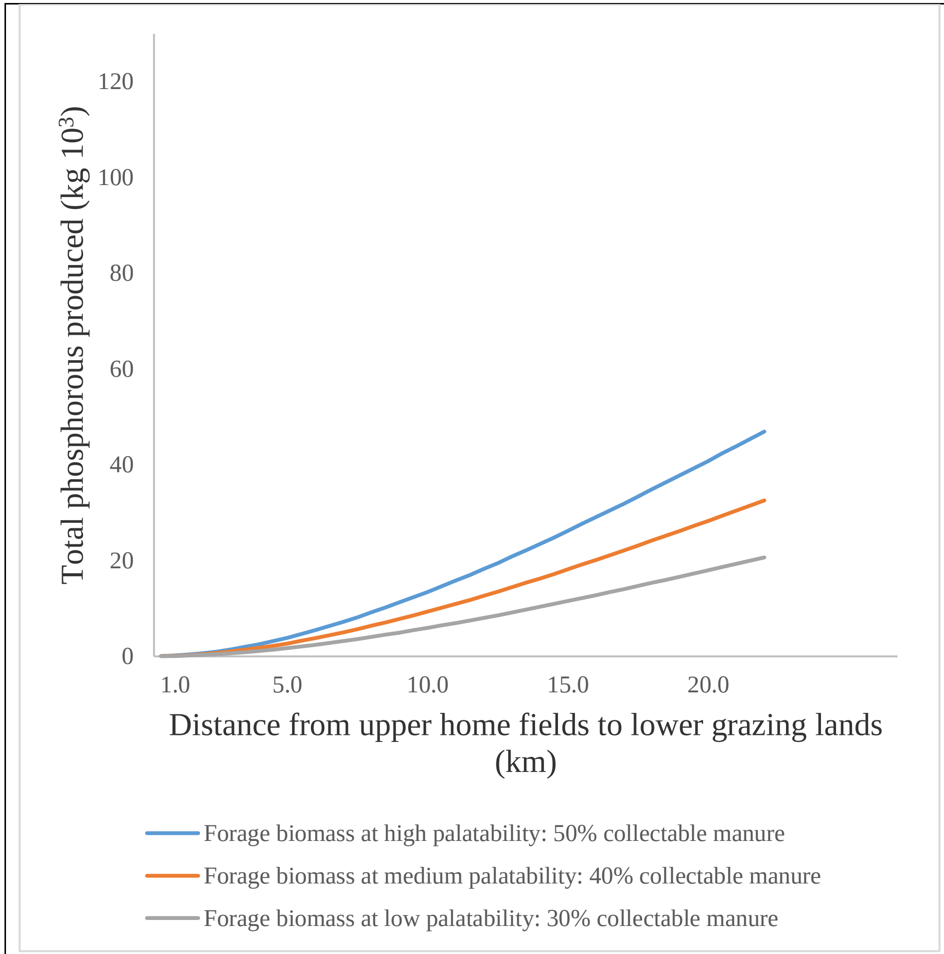
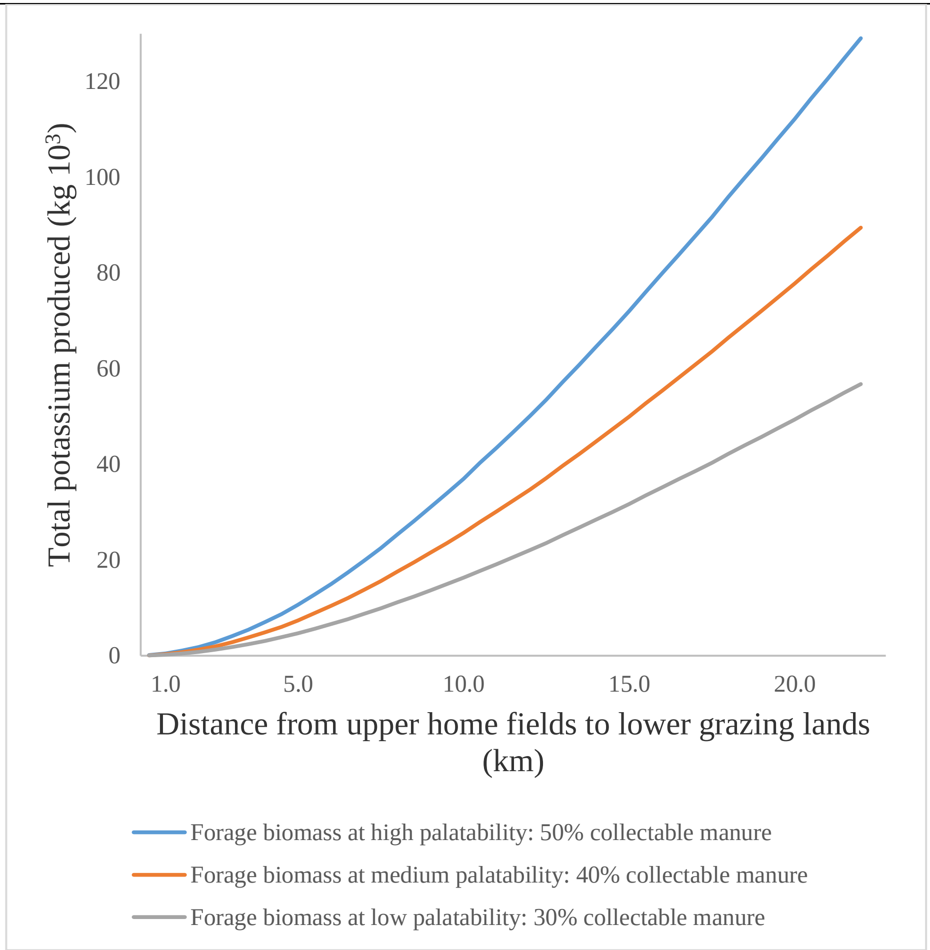
	

Figure 6-7: Phosphorous production from manure (P) (kg)	Figure 6-8: Potassium production from manure (K) (kg)

6.6.1.5 Long rain season scenario 1: Sole maize production

This involves the area of maize crop fields fertilized with livestock-mediated manure under the condition of balanced nitrogen fertilization. The area fertilized depends on the following: Palatability of forage biomass, collectable manure and the nutrient uptake of the crop. In the case of having high palatability forage and 50% collectable manure, the livestock-mediated manure from within 22 km distance, can fertilize maize crop area ranging from 1123 - 4220 ha (Figure 6-9). However, in the case of having medium palatability forage and 40% collectable manure, the livestock-mediated manure from within 22 km distance, can fertilize maize crop area ranging from 778 - 2926 ha (Figure 6-10).

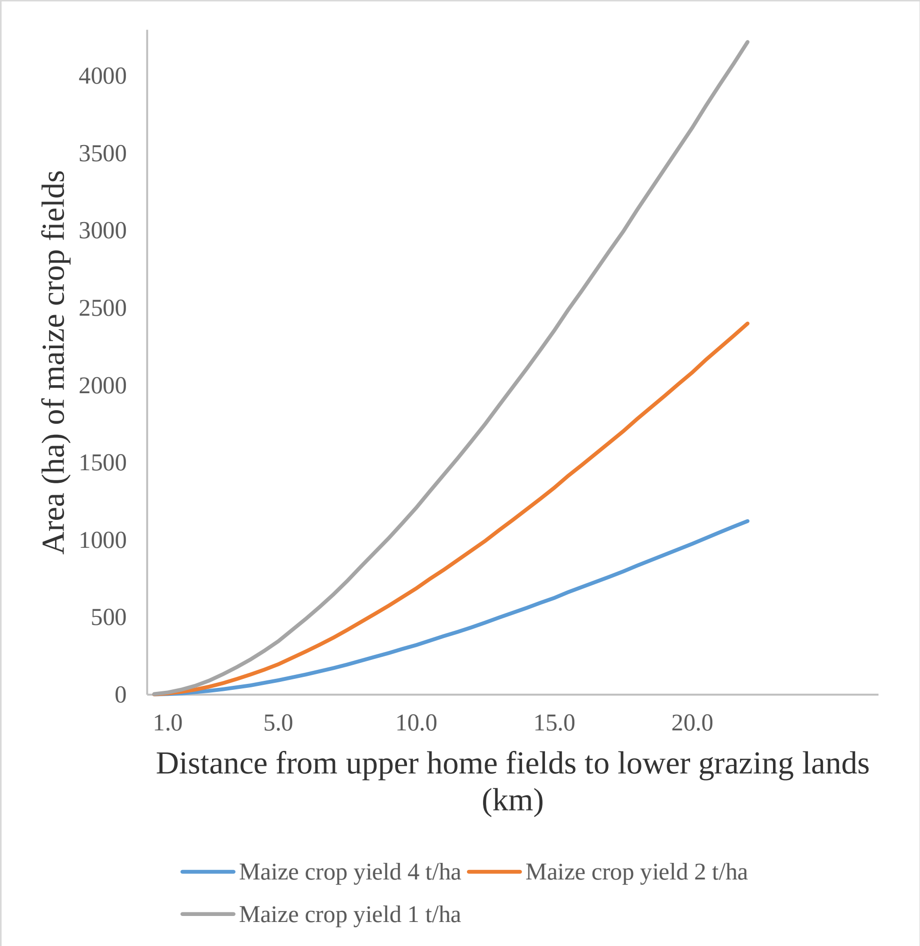


Figure 6-9: Area of maize crop fields fertilized under high palatability forage and 50% collectable manure

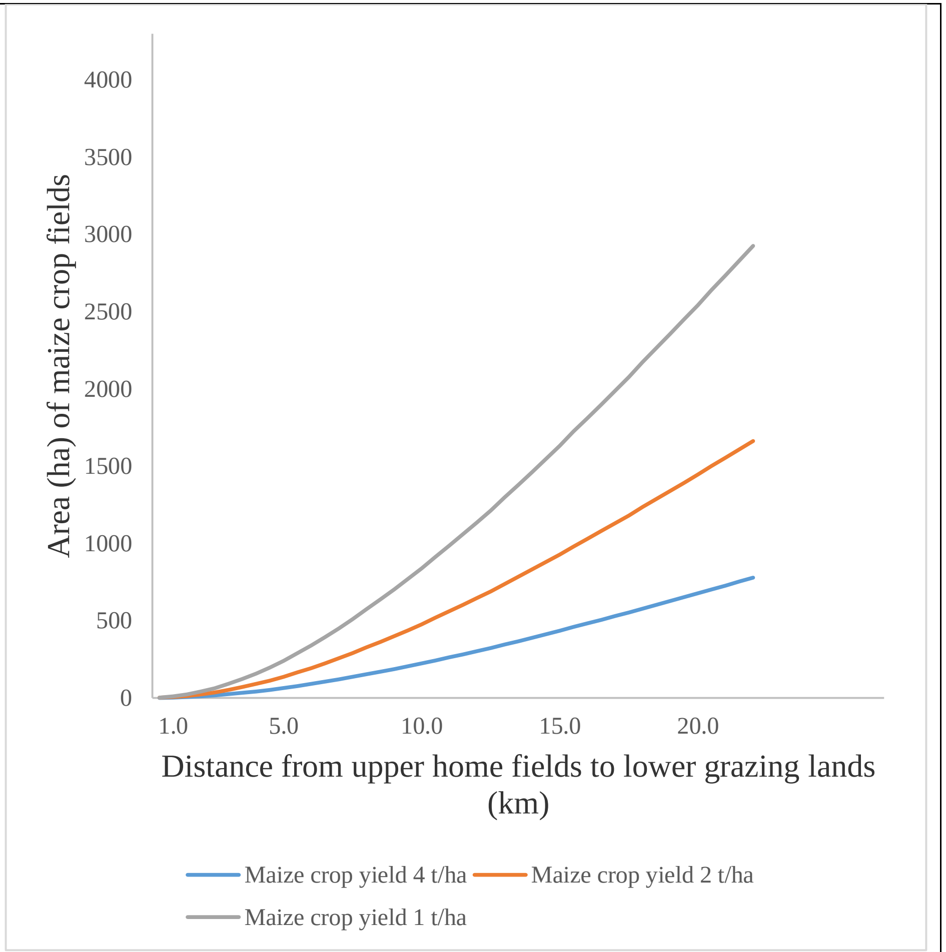


Figure 6-10: Area of maize crop fields fertilized under medium palatability forage and 40% collectable manure

In the case of having low palatability forage and 30% collectable manure, the maize crop area fertilized is lowest. The manure from within 22 km distance can fertilize maize area ranging from 494 - 1857 ha (Figure 6-11).

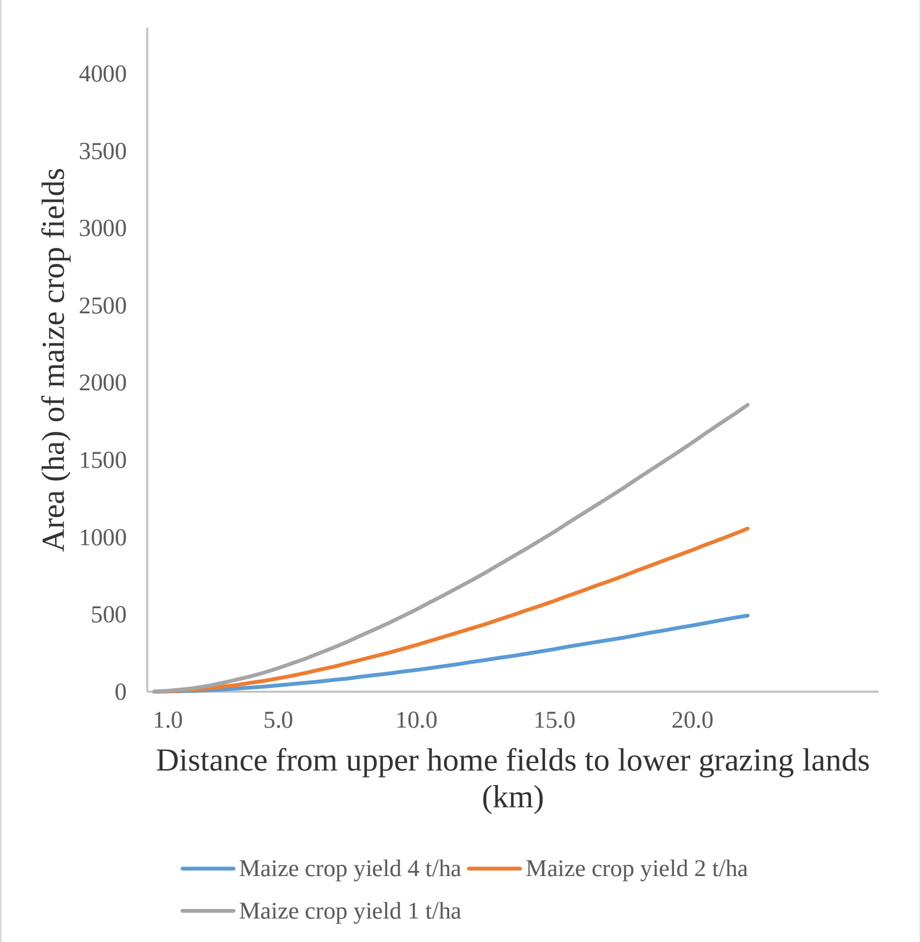


Figure 6-11: Area of maize crop fields fertilized under low palatability forage and 30% collectable manure

In all the cases, the area of maize fields fertilized by livestock-mediated manure depends on the yield value and the distance into the grazing lands. If the target value of maize grain yields is ≥ 4 t/ha, using manure from within 22 km distance into the grazing lands, the crop area fertilized is smaller. However, with maize grain yields value of ≤ 2 t/ha, the area fertilized is higher.

6.6.1.6 Long rain season scenario 2: Sole beans production

This involves the area of bean fields fertilized with livestock-mediated manure under balanced nitrogen fertilization. The area varies with the following: In the case where the forage palatability is high and 50% of manure produced is collected, the area of bean crop fields fertilized is higher. The livestock-mediated manure from within a distance of 22 km can fertilize 2370 - 7109 ha of bean crop fields (Figure 6-12). When the palatability of forage biomass is medium and collectable manure is 40%, the livestock-mediated manure collected from within 22 km distance can fertilize area of bean crop fields ranging from 1643 – 4929 ha (Figure 6-13).

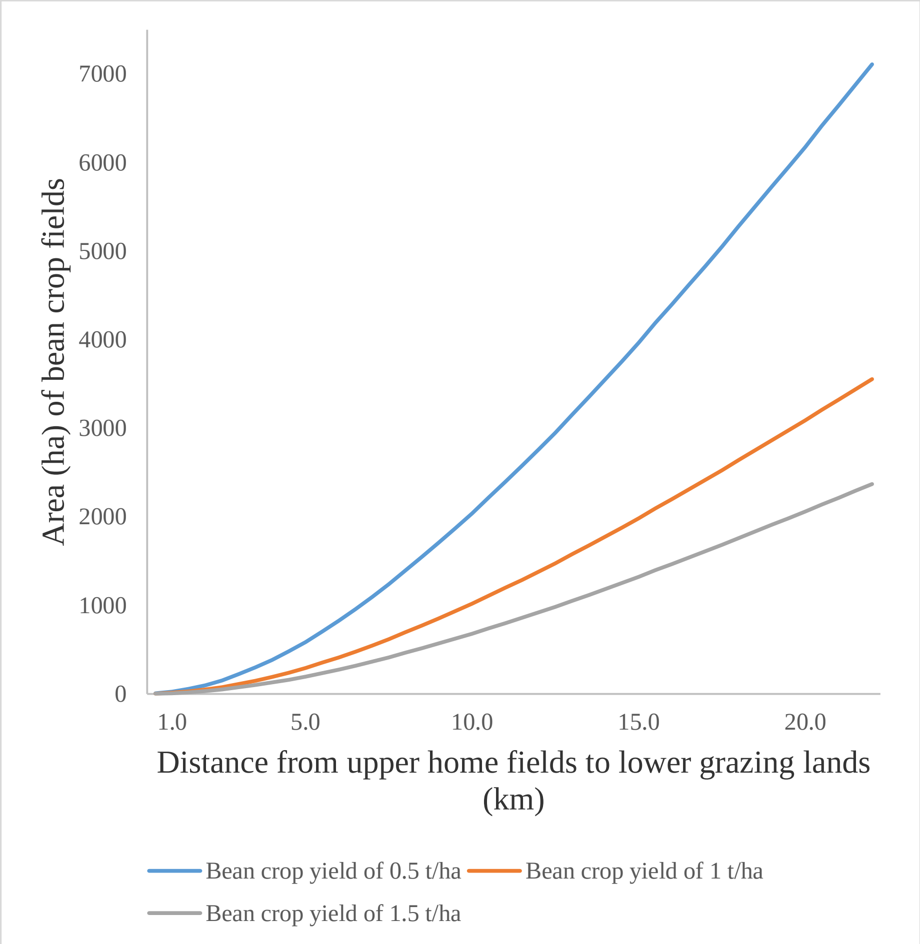


Figure 6-12: Area of bean crop fields fertilized under high palatability forage and 50% collectable manure

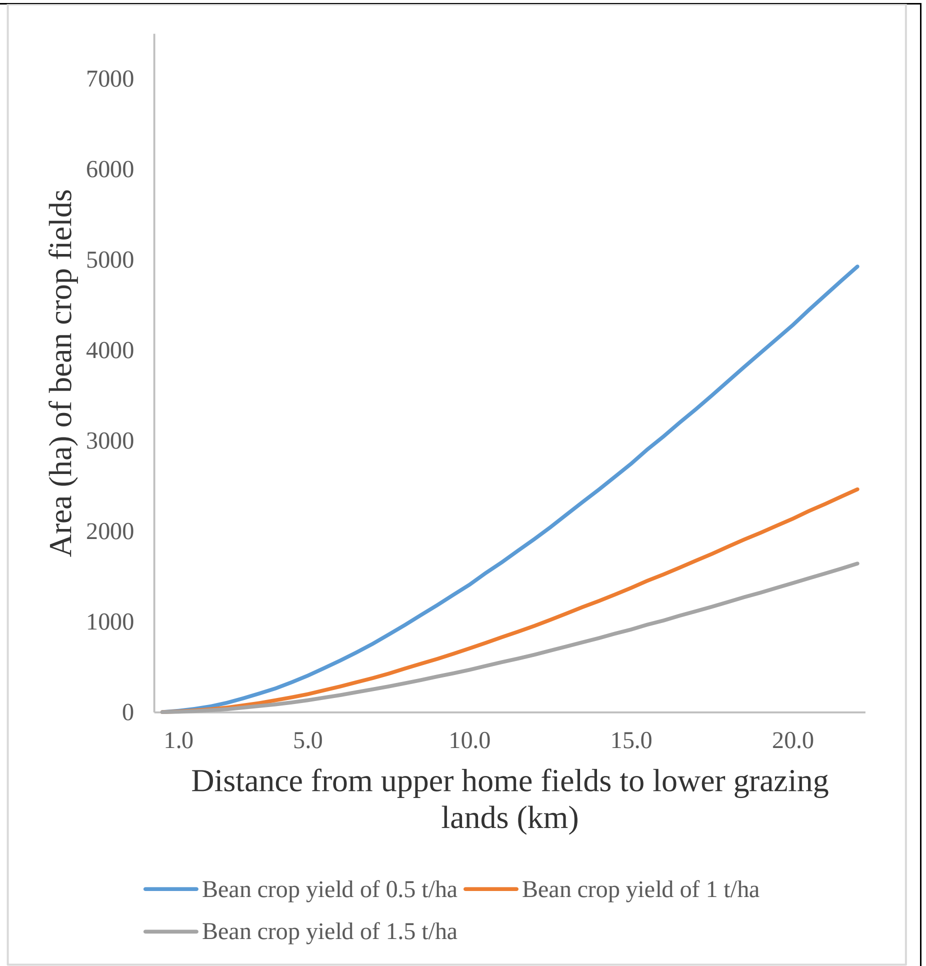


Figure 6-13: Area of bean crop fields fertilized under medium palatability forage and 40% collectable manure

In the case where forage palatability is low, and the collectable manure is 30%, the cropland area fertilized is also lower. The livestock-mediated manure collected from within 22 km distance can fertilize area of bean crop fields ranging from 1043 - 3128 ha (Figure 6-14).

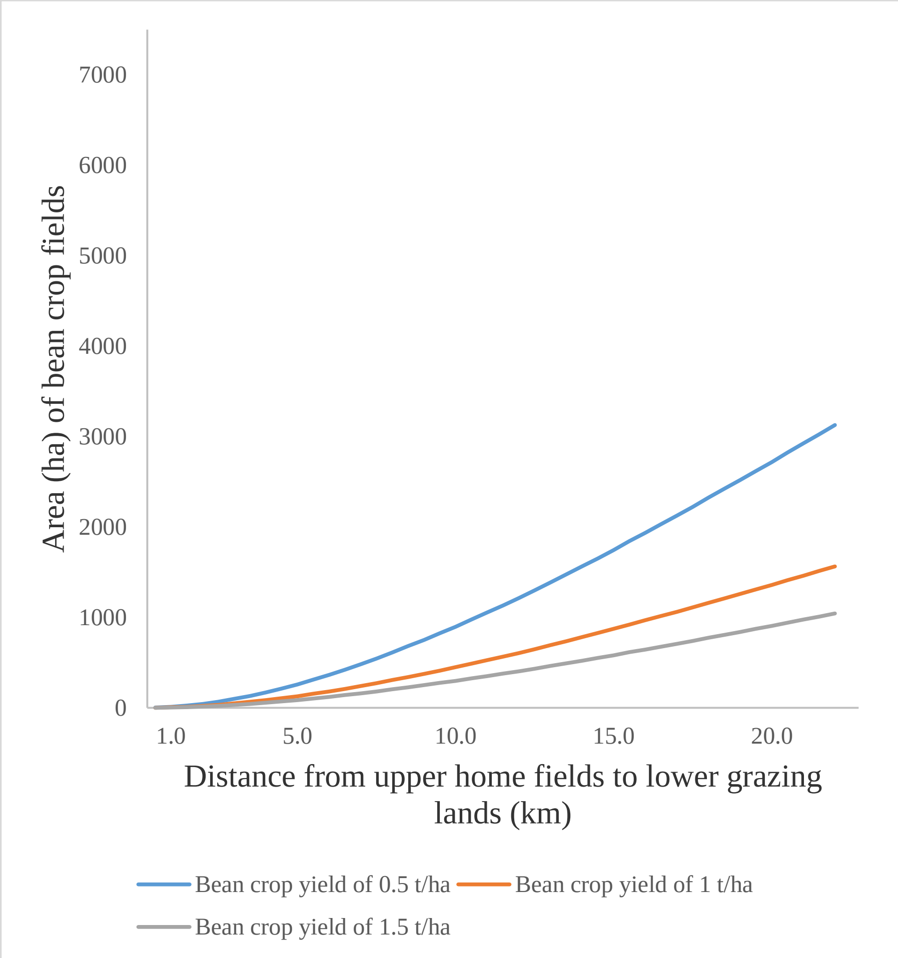


Figure 6-14: Area of bean crop fields fertilized under low palatability forage and 30% collectable manure

6.6.1.7 Long rain season scenario 3: Maize-bean rotations

Two-year maize-bean rotations

This is a two-year maize-bean rotations under balanced nitrogen fertilization. It involves 50% size of land under maize crop and 50% size of land under beans crop (Figures 6-15, 6-16 and 6-17). In the case of high palatability of forage biomass and 50% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 1524 - 5297 ha of maize-bean crop fields (Figure 6-15). However, under the conditions of medium palatability forage and 40% collectable manure, it can fertilize 1056 - 3673 ha of maize-bean crop fields (Figure 6-16).

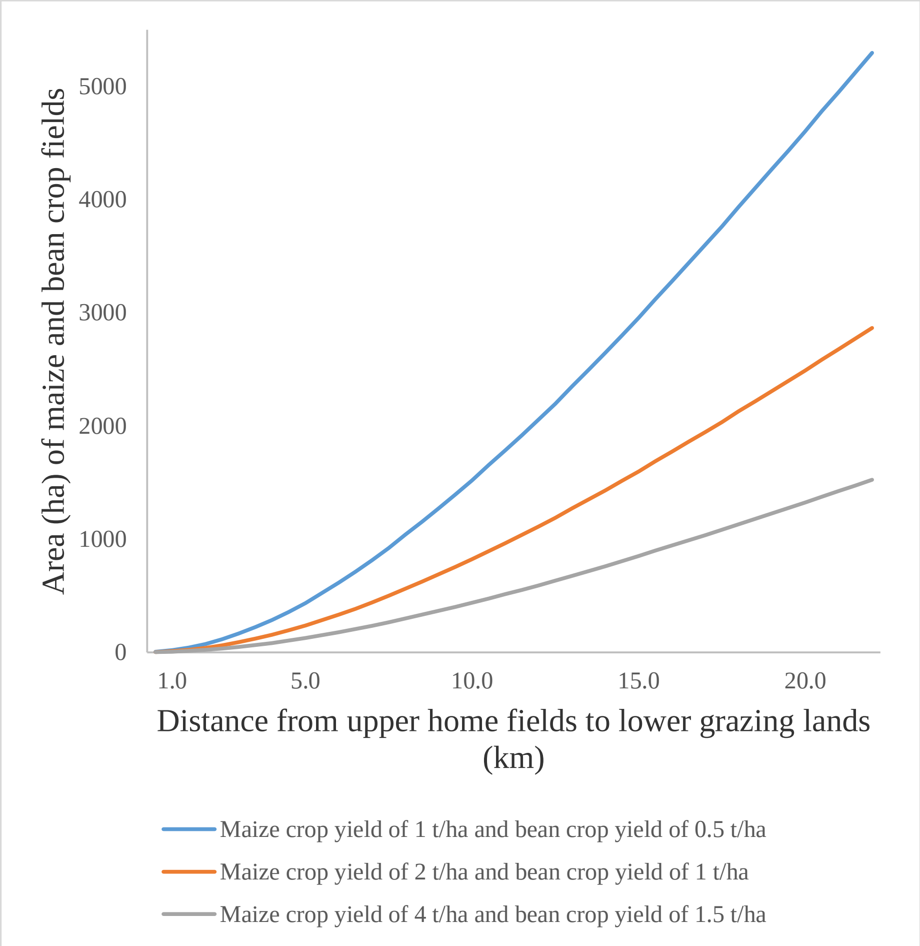
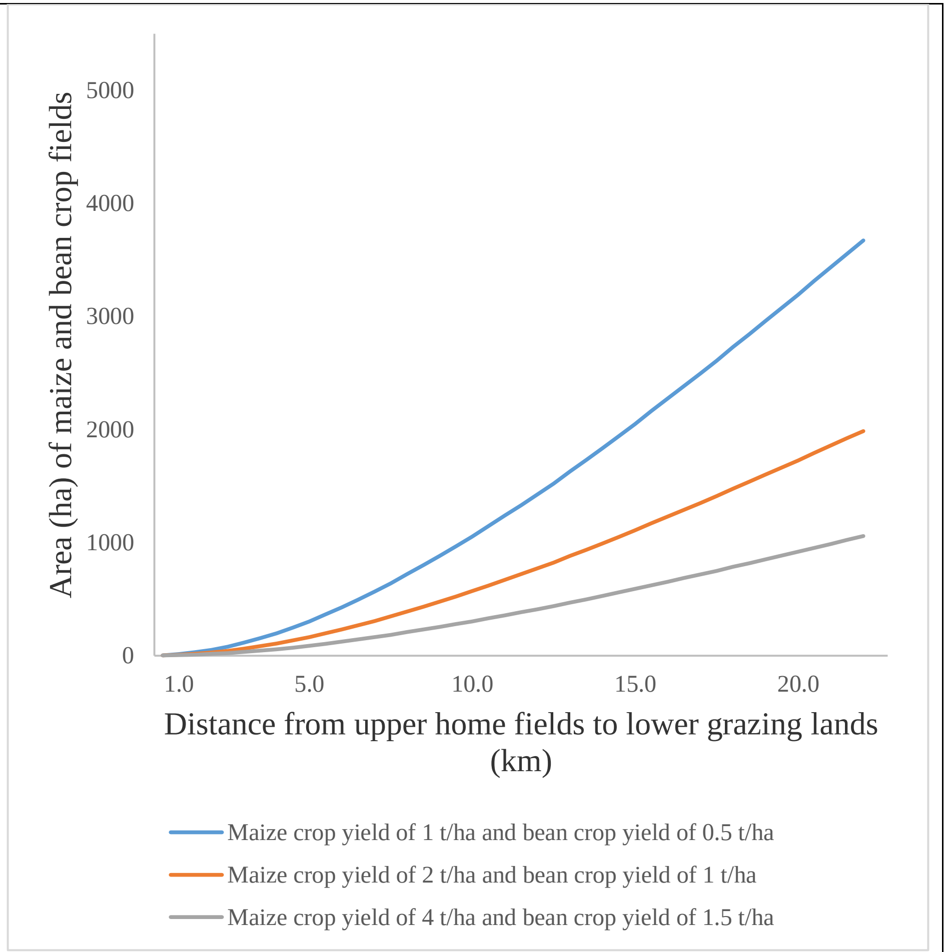
	

Figure 6-15: 50% maize fields-50% bean fields fertilized under high palatability forage and 50% collectable manure	Figure 6-16: 50% maize fields-50% bean fields fertilized under medium palatability forage and 40% collectable manure

In the case of low palatability forage and 30% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 670 - 2331 ha of maize-bean crop fields (Figure 6-17).

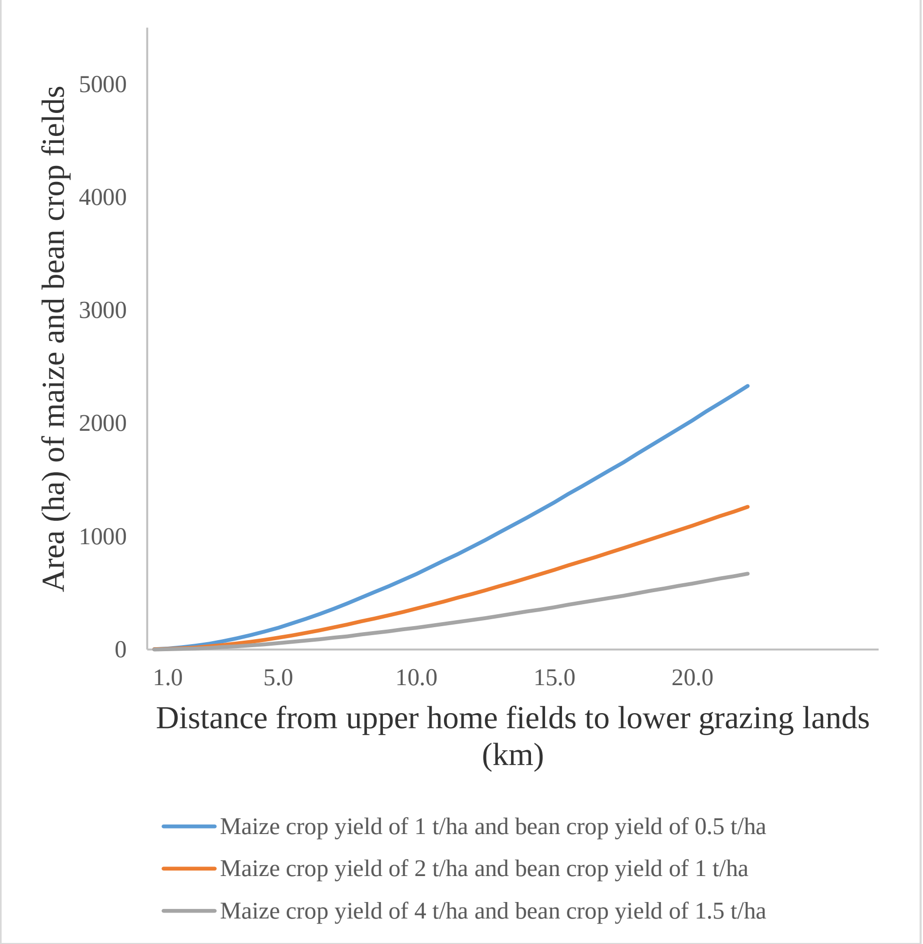


Figure 6-17: 50% maize fields-50% bean fields fertilized under low palatability forage and 30% collectable manure

Three-year maize-bean rotations

This is a three-year maize-bean rotations under balanced nitrogen fertilization. It is a case of 66% cropland under maize production and 34% of cropland under beans production (Figures 6-18, 6-19 and 6-20). In the case of high palatability forage biomass and 50% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 1362 - 4879 ha of maize-bean crop fields (Figure 6-18). In the case of medium palatability forage and 40% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 944 - 3382 ha of maize-bean crop fields (Figure 6-19).

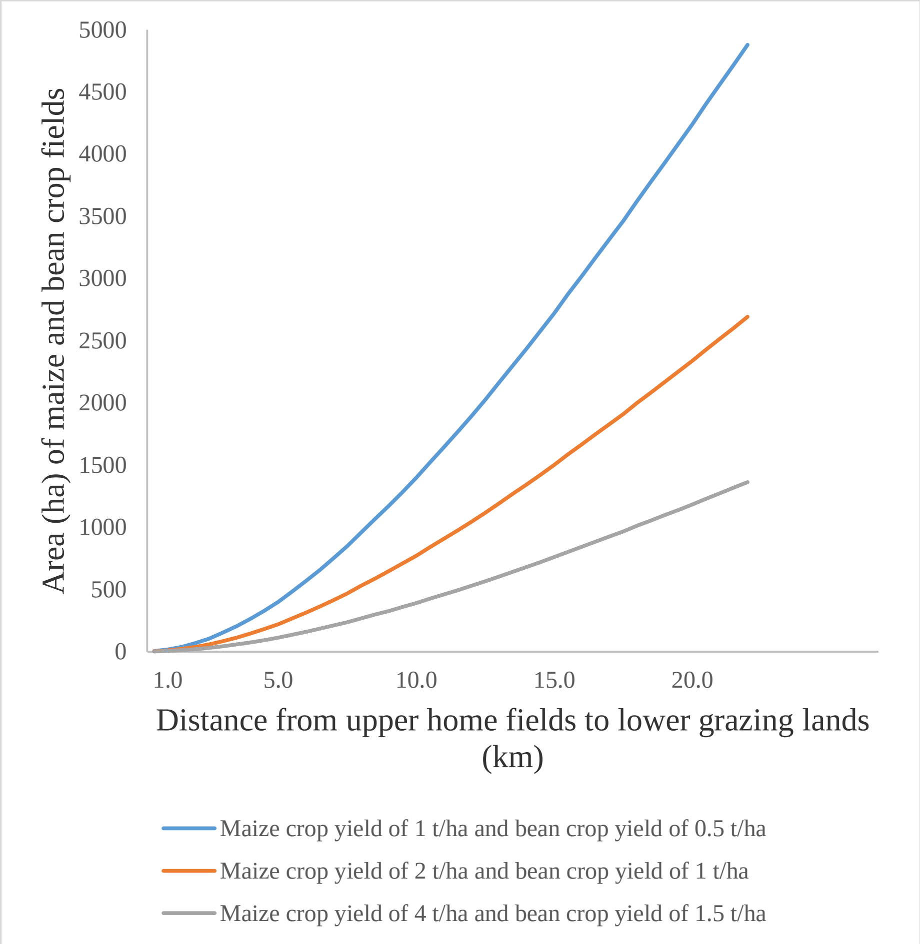


Figure 6-18: 66% maize fields-34% bean fields fertilized under high palatability forage and 50% collectable manure

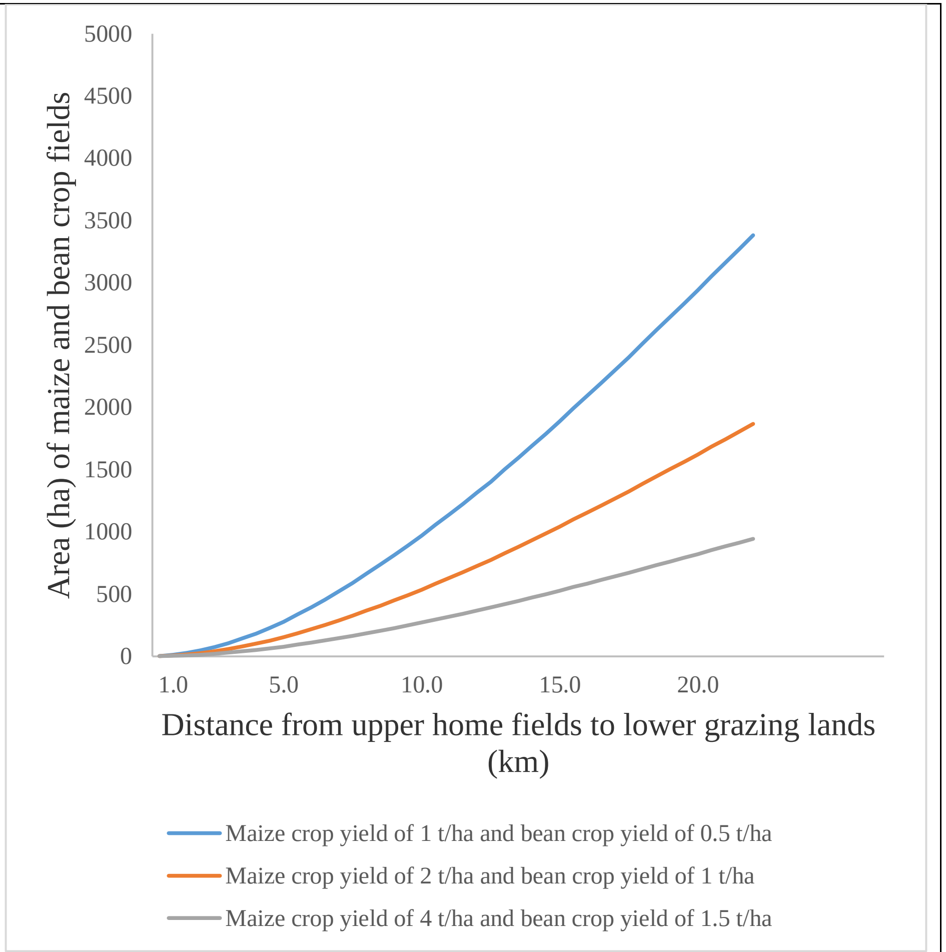


Figure 6-19: 66% maize fields-34% bean fields fertilized under medium palatability forage and 40% collectable manure

In the case of low palatability forage and 30% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 599 - 2147 ha of maize-bean crop fields (Figure 6-20).

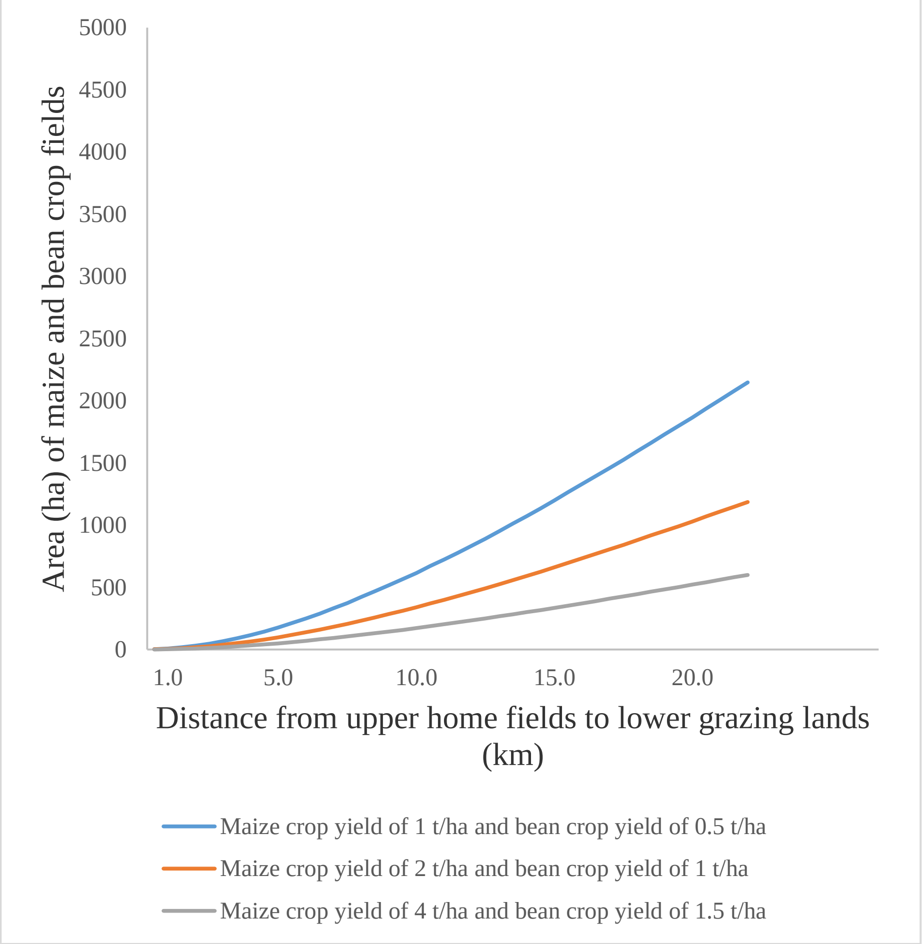


Figure 6-20: 66% maize fields-34% bean fields fertilized under low palatability forage and 30% collectable manure

Four-year maize-bean rotations

This involves four-year maize-bean rotations under the condition of balanced nitrogen fertilization. It is a farming system where 75% of cropland are under maize production while 25% of cropland are under beans production (Figures 6-21, 6-22 and 6-23). In the case of high palatability forage and 50% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 1293 - 4693 ha of maize-bean crop fields (Figure 6-21). However, in the case of medium palatability forage and 40% collectable manure, it can fertilize 896 - 3254 ha of maize-bean crop fields, with manure from same distance (Figure 6-22).

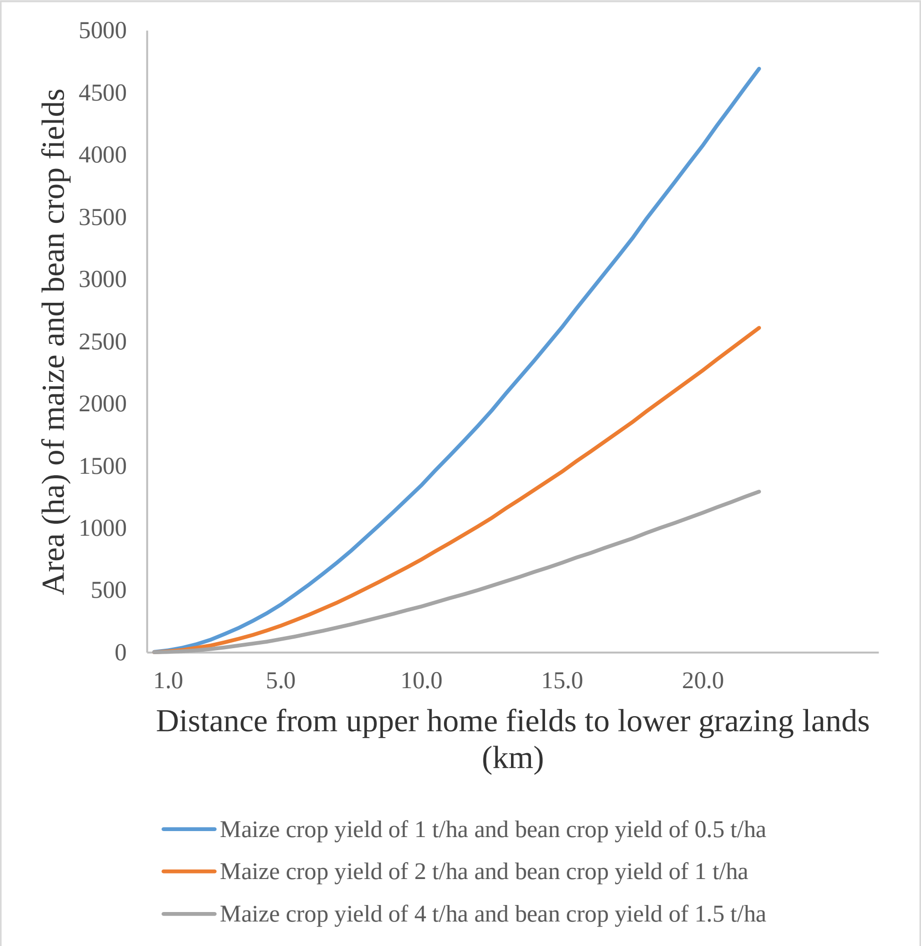


Figure 6-21: 75% maize fields-25% bean fields fertilized under high palatability forage and 50% collectable manure

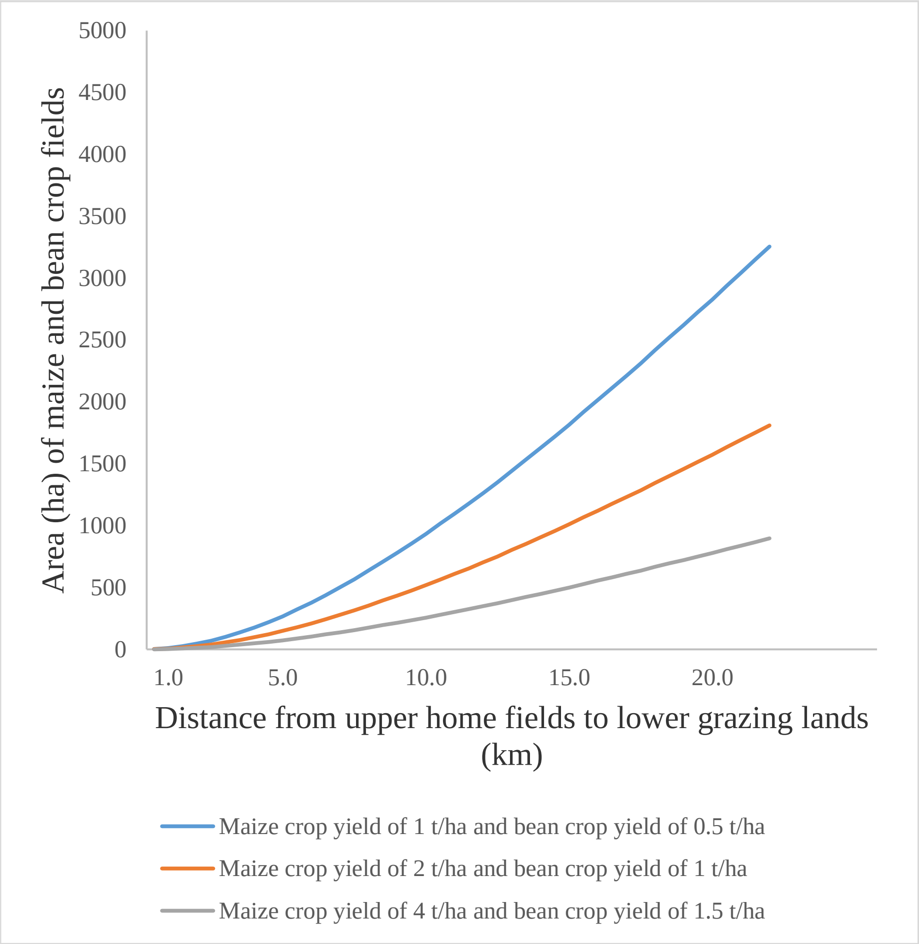


Figure 6-22: 75% maize fields-25% bean fields fertilized under medium palatability forage and 40% collectable manure

In the case of low palatability forage and 30% collectable manure, livestock-mediated manure from within a distance of 22 km can fertilize 569 - 2065 ha of maize-bean crop fields (Figure 6-23).

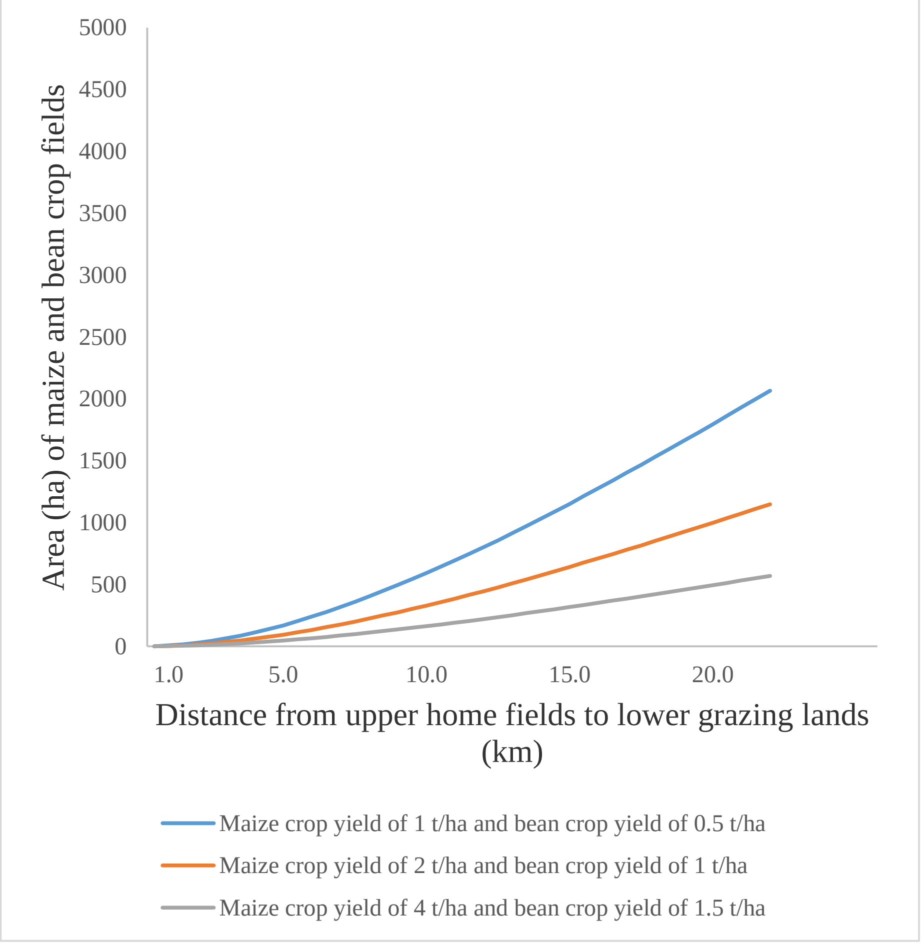


Figure 6-23: 75% maize fields-25% bean fields fertilized under low palatability forage and 30% collectable manure

6.6.1.8 Area of crop fields fertilized during long rain season: Using manure collected from distant grazing

This involves manure collected from half circular area within 22 km radius of grazing. The area fertilized is under long rain season yield production scenario, and under balanced nitrogen. The area of crop fields fertilized is higher with low nitrogen uptake and less area of crop fields in case of higher nitrogen uptake. The crop area fertilized ranges from 494 - 7109 ha (Table 6-7).

Table 6-7: Area (ha) of crop fields fertilized from distant collection (22 km) of manure under the scenario of long rain season yield production

Scenarios	High palatability forage:50% collectable manure			Medium palatability forage :40% collectable manure			Low palatability forage:30% collectable manure		
	Low yield	Medium yield	High yield	Low yield	Medium yield	High yield	Low yield	Medium yield	High yield
	Area of crops fertilized (ha)			Area of crops fertilized (ha)			Area of crops fertilized (ha)		
Sole maize production	4220	2399	1123	2926	1664	778	1857	1056	494
Sole beans production	7109	3554	2370	4929	2464	1643	3128	1564	1043
50% land maize and 50% land beans rotation (Two-year rotations)	5297	2865	1524	3673	1987	1056	2331	1261	670
66% land maize and 34% land beans rotation (Three-year rotations)	4879	2691	1362	3382	1866	944	2147	1184	599
75% land maize and 25% land beans rotation (Four-year rotations)	4693	2610	1293	3254	1810	896	2065	1149	569

6.6.1.9 Economic viability of transporting manure from distant grazing lands

Travelling for a distance of 35 km and returning with a manure to same starting point equals a distance of about 70 km, and the estimated fuel cost for this distance is £37 (Table 6-8). A truck that can be available to Marsabit-central farmers carry a manure-load of 4 tons in one round. Manure weighing 4 tons contain 80 kg of nitrogen. 80 kg of mineral nitrogen is estimated to cost £39 in the nearest market. It is therefore economically viable to transport livestock manure from a maximum one-way distance of 35 km. This analysis does not allow for vehicle depreciation and hire costs, but on this basis, all the forgoing analysis for 22 km maximum range seems reasonable.

Above a distance of 22 km, it is financially better for farmers to buy mineral fertilizer.

Table 6-8: Cost of transporting manure from a distant grazing lands

One-way distance from crop fields to grazing lands (km)	Cost of fuelling truck (KES)	Cost of fuelling truck (GBP)
10	1500	11
20	3000	21
30	4500	32
40	6000	42

6.6.2 Collection of manure only from local grazing in long rain season

This involves collection of manure from half-circle area with a radius up to 7 km grazing distance. This happens when farmers have no capacity of distant transportation or are not willing to utilize distant manure.

6.6.2.1 Forage biomass production and TLUs supported by local grazing: Long rain season

Seven kilometre grazing distance of long rain season produces cumulative forage biomass of $13.0 * 10^6$ kg and this feeds TLUs of about $11.0 *10^3$ (Table 6-9).

Table 6-9: Cumulative forage biomass produced from within 7 km grazing distance and number of TLUs supported by forages

Distance (km)	Cumulative forage biomass at high palatability	
	Forage biomass (kg)	Number of TLUs supported by forage biomass for 200 days
1	303,388	243
3.5	3,602,536	2,882
5.5	8,495,446	6,796
7.0	13,189,947	10,552

6.6.2.2 Manure production from local grazing: Long rain season

Assuming grazing distance of 7 km, the total DM manure produced in long rain season is 3.6 * 10^6 kg, and the collectable manure is about 1.8 * 10^6 kg (Table 6-10).

Table 6-10: Total dry manure production and collectable manure

Distance (km)	Forage biomass at high palatability	
	Manure (dry) produced by livestock (kg)	50% collectable dry manure (kg)
1	83,007	41,503
3.5	985,654	492,827
5.5	2,324,354	1,162,177
7.0	3,608,770	1,804,385

6.6.2.3 Nutrients production from local grazing: Long rain season

The nutrients production from within 7 km grazing distance involve 36.0 * 10^3 kg, 7.0 * 10^3 kg, and 20.0 * 10^3 kg of nitrogen, phosphorous and potassium, respectively (Table 6-11).

Table 6-11: Nutrients production from collectable manure of local grazing: Long rain season

Distance (km)	Forage biomass at high palatability: 50% collectable manure	Forage biomass at high palatability: 50% collectable manure	Forage biomass at high palatability: 50% collectable manure
	Nitrogen (N) production (kg)	Phosphorous (P) production (kg)	Potassium (K) production (kg)
1	830	166	457
3.5	9,857	1,971	5,421
5.5	23,244	4,649	12,784
7.0	36,088	7,218	19,848

6.6.2.4 Area of crop fields fertilized by manure collected from local grazing in long rain season

This involves fertilization of crop fields under the long rain season yield scenario. The area of crop fields that can receive manure from local grazing of long rain season ranges from 173 - 1093 ha. The area is lower than the area of crop fields fertilized when the distant manure is used for fertilization. The area of crop fields fertilized differs with the nitrogen uptake of crops. Smaller area of crop fields can be fertilized, if scenarios with high nitrogen uptake, including sole maize production, three-year and four-year maize-bean rotations are adopted with local collection of manure. However, the yield scenarios with low nitrogen-uptake, including two-year maize-bean rotations and sole beans production have higher fertilizable area of crop fields (Table 6-12).

Table 6-12: Area (ha) of crop fields fertilized from local collection of manure under the scenario of long season yields production

Scenarios	Forage biomass at high palatability:50% collectable manure		
	Low yield	Medium yield	High yield
	Area of crops fertilized (ha)		
Sole maize production	649	369	173
Sole beans production	1093	547	364
50% land maize and 50% land beans rotation	815	441	234
66% land maize and 34% land beans rotation	750	414	209
75% land maize and 25% land beans rotation	722	401	199

6.6.3 Collection of manure from local grazing in short rain season

This involves season of limited rainfall. Larger number of livestock moves to further distance in search of water and pasture. Hence, manure in the distant grazing lands is not collectable. However, some livestock are left for local grazing in home-based pasture fields. Local grazing of this season involves grazing within semi-circular area with a radius of 7 km. In this season, local grazing provides manure for fertilization of crop fields under the nitrogen demand of short rain season scenario.

6.6.3.1 Forage biomass production from local grazing: Short rain season

The forage biomass is produced from within the total area of 7693 ha. The producible cumulative DM forage biomass in the short season is $11.0 * 10^6$ kg (Table 6-13).

Table 6-13: Forage biomass production during short rain season in local home fields

Rainfall (mm)	RUE (kg/ha/mm)	Forage production (kg/ha)	Distance in to the grazing lands (km)	Forage palatability along the transect (%)	Palatable forage biomass (kg/ha)	Area (ha)	DM forage production (kg)
			1	74	1473	157	231,198
			2	74	1473	471	693,595
			3	73	1453	785	1,140,370
228	8.7	1990	4	72	1433	1099	1,574,647
			5	71	1413	1413	1,996,428
			6	71	1413	1727	2,440,078
			7	70	1393	2041	2,843,113

6.6.3.2 Nutrients production from short season rainfall

The cumulative forage biomass produced in short rain season from within a grazing distance of 7 km, can support 11.0 x 10^3 TLUs. The livestock-mediated manure from this season produces 30.0 x 10^3 kg, 6.0 x 10^3 kg, 16.0 x 10^3 kg of nitrogen, phosphorous and potassium, respectively.

The low rainfall in short season results in less amount of nutrients production than in the long rain season (Table 6-14).

Table 6-14: NPK production in short rain season

Cumulative forage biomass (kg)	Number of TLUs fed in 165 days	Manure (dry) production (kg/165 days)	50% Collectable (dry) manure (kg)	Nitrogen (N) production (kg)	Phosphorous (P) production (kg)	Potassium (K) production (kg)
10,919,429	10,589	2,987,556	1,493,778	29,876	5,975	16,432

6.6.3.3 Area of crop fields fertilizable in short rain season

The area of crop fields fertilized varies with the nitrogen uptake of various production scenarios. The area is under nitrogen uptake of short rain season yield production scenario. The nitrogen uptake of short rain season yield scenario is lower than the nitrogen uptake in long rain season yield scenario.

The area of crop fields fertilized is lower in short rain season compared to the area fertilized in long rain season. This is due to low manure production in short rain season, resulting in lesser production of NPK. Under high yield scenario, less hectares of crop fields are fertilized than under medium and low yield scenarios (Table 6-15).

Table 6-15: Area (ha) of crop fields fertilized using local manure from upper home fields: Short rain season

Scenarios	Low yield	Medium yield	High yield
Sole maize production	1129	537	390
Sole beans production	1113	648	453
50% land maize and 50% land beans rotation	1121	588	419
66% land maize and 34% land beans rotation	1124	570	408
75% land maize and 25% land beans rotation	1125	561	404

6.6.4 Nutrient balance

This is NPK balance under the scenarios of long rain season and short rain season yields production. Long rain season yield scenario has high nitrogen uptake and therefore utilize nutrients from local and distant grazing lands. However, the nitrogen uptake in short rain season scenario is lower and utilize nutrients from only local grazing. The primary inputs and outputs were used for the calculation of nutrients balance. These include nutrient inflows through manure, nutrient outflows through maize and bean grains as well as maize and beans non-food biomass. In all the scenarios, nitrogen was balanced, phosphorous was positively balanced while potassium shows negative balance.

6.6.4.1 Nutrient balance under long rain season yields scenario

The target is to maintain long-term nitrogen balance. This leads to positive phosphorous balance and negative potassium balance. The positive phosphorous balance and the negative potassium balance are higher in high yield scenario than in medium and low yield scenarios. The phosphorous balance ranges from 2.41 to 12.10 kg/ha and the potassium balance ranges from -15.07 to -185.35 kg/ha. The scenarios of sole maize production, three-year and four-year maize-bean rotations have more negative potassium balance. However, sole beans production and two-year maize-bean rotations have less negative potassium balance (Table 6-16). In median long rain season, balanced nitrogen fertilization for all the area of crop fields in Marsabit-central is attainable.

Table 6-16: NPK balance under long rain season yields scenario

Scenarios	Low yield			Medium yield			High yield		
	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)
Sole maize production	0.00	3.22	-49.62	0.00	5.66	-86.11	0.00	12.10	-185.35
Sole beans production	0.00	2.41	-15.07	0.00	4.82	-30.15	0.00	7.23	-45.22
50% land maize/50% land beans	0.00	2.81	-32.35	0.00	5.24	-58.14	0.00	9.66	-115.30
66% land maize/34% land beans	0.00	2.95	-38.10	0.00	5.38	-67.46	0.00	10.47	-138.67
75% land maize/25% land beans	0.00	3.03	-40.96	0.00	5.46	-72.10	0.00	10.88	-150.32

6.6.4.2 Nutrient balance under short rain season yields scenario

This is the balance of nutrients when the local manure from upper home fields is used. This nutrient balance occurs during short rain season, with the use of manure from within a radius of 7 km grazing distance. Whilst the nitrogen nutrient is balanced, the phosphorous balance ranges from 1.53 to 4.82 kg/ha and the potassium balance ranges from -12.50 to -67.87 kg/ha. Comparatively, the negative potassium balance is more pronounced in the scenarios of sole maize production, and four-year maize-bean rotations than other scenarios. Generally, the nutrient balance in short rain season yield scenario is lower than the balance in long rain season yield scenario. This is due to high nutrient uptake in long rain season yield scenario than in short rain season yield scenario (Table 6-17). In median short rain season, the local collectable manure can balance nitrogen for about 1000 ha of crop fields, less than the area of crop fields in Marsabit central production systems.

Table 6-17: NPK balance under short rain season yields scenario

Scenarios	Low yield			Medium yield			High yield		
	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)	N balance (kg/ha)	P balance (kg/ha)	K balance (kg/ha)
Sole maize production	0.00	1.53	-23.50	0.00	3.22	-49.62	0.00	4.44	-67.87
Sole beans production	0.00	1.93	-12.50	0.00	3.37	-20.96	0.00	4.82	-30.15
50% land maize/50% land beans	0.00	1.73	-17.99	0.00	3.30	-35.29	0.00	4.63	-49.01
66% land maize/34% land beans	0.00	1.66	-19.83	0.00	3.27	-40.07	0.00	4.57	-55.29
75% land maize/25% land beans	0.00	1.63	-20.75	0.00	3.26	-42.46	0.00	4.54	-58.44

6.6.5 Ratio of grazing land to crop land

The ratio of grazing land to crop land is based on the nutrients uptake under the long rain season yield scenario. This is when manure collection from distant grazing lands is possible. The demand of grazing land to fertilize crop land increases with the increasing crop productivity. High yield maize productivity of 4.0 t/ha (high yield scenario) requires more hectares of grazing lands for fertilization than the maize productivity of 1.0 t/ha (low yield scenario) and 2.0 t/ha (medium yield scenario). The demand of grazing lands by sole beans production and two-year maize-bean rotations is lower than the demand of other production scenarios (Table 6-18).

Table 6-18: Area of grazing lands required to fertilize crop land under different production scenarios

Scenarios	Low yield			Medium yield			High yield		
	High palatability forage and 50% collectable manure	Medium palatability forage and 40% collectable manure	Low palatability forage and 30% collectable manure	High palatability forage and 50% collectable manure	Medium palatability forage and 40% collectable manure	Low palatability forage and 30% collectable manure	High palatability forage and 50% collectable manure	Medium palatability forage and 40% collectable manure	Low palatability forage and 30% collectable manure
Sole maize fields _Grazing land: cropland ratio (ha)	18	26	41	32	46	72	68	98	154
Sole bean fields _ Grazing land: cropland ratio (ha)	11	15	24	21	31	49	32	46	73
50% land maize and 50% land beans rotation_ Grazing land: cropland ratio (ha)	14	21	33	27	38	60	50	72	113
66% land maize and 34% land beans rotation_ Grazing land: cropland ratio (ha)	16	22	35	28	41	64	56	80	127
75% land maize and 25% land beans rotation_ Grazing land: cropland ratio (ha)	16	23	37	29	42	66	59	85	134

6.7 Discussion

The low food crops yield in Marsabit-central farms is attributable at least in part to minimal use of manure and non-use of mineral fertilizer. Manure is the affordable input that can improve food production and reverse the current trend of nitrogen depletion. Efficient use of livestock manure can allow Marsabit-central farmers to live within their means and also promotes sustainable food production.

The locally available manure and the manure in the distant grazing lands offer the opportunity for sustainable food production. Local manure can be acquired at less cost than the distant manure. However, the longer the distance into the grazing lands, the higher the accumulative manure from the grazing lands.

Crop-livestock farmers need to consider the location to graze the livestock and possibility of utilizing distant manure. Harmonising the period of manure collection and grazing itinerary can ease the logistics of collecting manure.

Livestock mobility and the collectable manure: The seasonality of the rainfall affects the grazing itinerary of livestock, thus affecting the accessibility of manure. The seasonal rainfall determines the number of TLUs that can be fed. This work showed that the area of study can feed 50 – 69 x 10^3 TLUs in median long rain season. The livestock department of Marsabit County estimates zebu cattle of about 100,000 heads in Marsabit-central sub-county (GoK, 2013). 100,000 heads of zebu cattle can be around 60 - 80 x 10^3 TLUs. This shows that Marsabit-central grazing lands can feed its livestock population under the median long rain season with 50% probability of exceedance, thus manure from local and distant grazing is accessible. Manure from local and distant grazing is sufficient for balanced nitrogen fertilization of all Marsabit-central crop fields. However, grazing distance of >7 km from the home crop fields into the grazing lands cannot allow livestock to spend in upper home fields *boma* at night. Livestock spends in the *boma* within the distant grazing lands, and farmers have an option of transporting the manure into the crop fields.

Local grazing in median short rain season, can feed 10.5 x 10^3 TLUs. The local grazing involves within 7 km grazing distance from home fields. In this case, livestock spends night in the home *boma*, and manure from *boma* is collectable at no or minimal cost. However, short rain season and low long rains occasionally requires some livestock to move to better and further grazing lands situated >22 km from home fields, making manure partially inaccessible.

Saving manure from the wet seasons: Under high forage palatability and 50% collectable manure, it is possible to save manure from wetter long seasons for fertilization in the season of manure limitation. Farmers can either apply manure to crop fields and the nutrient stock is built for the following cropping season or manure stored for the following cropping season. Therefore, manure produced in the local fields and distant grazing lands during wetter long seasons is sufficient and can provide surplus manure for fertilization in the season of limited manure.

Matching crop production practices with the collectable manure: In a variable environment, smart food production system is necessary. Farmers need to plant area of crop fields that can be supported by the quantity of collectable manure. The short rain season scenario has less nutrient demand and provides farmers with an option in the event of less collectable manure (Table 6-5). This is a case of manure collection only from local grazing. However, in the season with possibility of accessing manure from local and distant grazing, collectable manure supports more hectares of crop fields.

The report from government department of Agriculture in Marsabit indicates 1800 ha of crop farms in the area of study (Marsabit Central) (GoK, 2011a). The manure produced in upper local fields alone can support 400 -1,130 ha of crop fields, under less nutrient demand of short rain season yield scenario (Table 6.15). Also, local collection of manure fertilizes 170 -1,000 ha of crop fields under long rain season yield scenario (Table 6-12). Local collection of manure cannot solely support the all 1800 ha arable areas of Marsabit-central crop farms. However, a combination of manure from local and distant grazing lands can fertilize and balance the nitrogen flows in 1800 ha of Marsabit-central crop farms. Furthermore, utilization of manure both from local and distant grazing lands enable adoption of improved long season yield scenario.

Sole cropping systems: Firstly, increasing the productivity of sole maize grain yields to 4.0 t/ha and sole bean grain yields to 1.5 t/ha, results in either reduced area of crop fields to receive livestock manure or increased demand on distant manure. Secondly, in maintaining sole maize grain yields of 2.0 t/ha and sole bean grain yields of 1.0 t/ha, manure collected from within a distance of 22 km into the grazing lands can fertilize larger area of crop fields than the case of 4.0 t/ha sole maize grain yields and 1.5 t/ha sole bean grain yields (Table 6-7 and Table 6-12). Increase in crop productivity requires collection of manure from further grazing lands to meet crop-nutrient demand. This increases the cost of food production. Farmers need to consider the cost of manure collection and their target of improving crop productivity. It is rational for farmers to strive for maize and beans production scenarios that can be sustained over time. Sole maize cropping scenario has more nutrient demand, and may not be sustainable in the long-run. The manure resource sustains the maize-beans rotation systems more than the sole cropping systems.

Maize-bean rotations: The low grain yield rotation systems of ≤1.0 t/ha and ≤0.5 t/ha for maize and beans, respectively, cannot feed growing human population in Marsabit. The scenarios of high yield, under three-year and four-year maize-bean rotations increase the demand on livestock-mediated manure, while also increasing potassium mining from the soils. The two-year rotations of 50% land under maize and 50% land under beans practice is more promising (Table 6-7 and Table 6-16). Livestock-mediated manure can sustainably support the medium yield scenario, under two-year maize-bean rotation systems. This has lowest case of mining potassium nutrient, whilst also has the potential for nitrogen fixation. Previous studies have shown that common bean can fix nitrogen at about 17-57 kg/ha (Dakora and Keya 1997, Herridge, Peoples et al. 2008). Therefore, manure fertilization with two-year maize-bean rotations is sustainable and worth adoption.

Nutrient balance: The negative potassium balance is due to high uptake of potassium in crop grains and non-food crop biomass. As the crop grains and non-food crop biomass increases in high yield scenario, potassium uptake also increases, resulting in negative potassium balance. The finding on negative potassium balance in fully fertilized crop fields has also been reported elsewhere (Mafongoya, Chirwa et al. 2005, Ajayi, Place et al. 2011). Manning (2010), reported that US$5600 million per year is required to replenish soil stocks of potassium in Africa. A continental-level study has also shown negative potassium balance across African agricultural systems (Sheldrick, Syers et al. 2002). Similarly, the demand of potassium fertilizer in SSA has been predicted to increase annually at 7.11% within the year 2015-2020. Likewise, by the year 2020 the potential nutrients balance (thousand tonnes) in Africa are estimated at 4304, 7204, and -997 for nitrogen, phosphorous and potassium, respectively (http://www.fao.org/3/a-i6895e.pdf, accessed 11th April, 2018). The predicted increase of demand in potassium fertilizer is due to expected increase in quantity of harvested products (food grains and non-food biomass), to feed growing human population. The increasing crop grains and non-food crop biomass results in negative potassium balance.

However, other potential sources of nutrient can maintain the potassium balance. In Marsabit-central, incorporation of non-palatable forage biomass from grazing lands, mulching, and the unused part of khat plant for potassium fertilization is worth researching. Wood ash is also potential contribution to the potassium fertilization of soils. Demeyer, Nkana et al. (2001), showed that wood ash contains 29 - 41 x 10^3 mg/kg of potassium. This work revealed that a household in Marsabit-central produces 8 kg of wood ash per month. Efforts toward utilization of wood ash and other potential sources of potassium fertilizer is required.

In addition, potassium nutrient is less yield-restraining than nitrogen and phosphorous nutrients (Smaling 1993). Also, the potassium concentrations in the crop-fields of Marsabit-central is not deficient at the time of study. Consistently, Kaizzi, Cyamweshi et al. (2018), reported non-deficiency of potassium nutrient in other part of Kenya. In spite of negative potassium balance, the livestock-mediated manure balanced the deficient nitrogen nutrient in Marsabit-central farms.

Positive phosphorous balance: The result shows low ranges of positive phosphorous balance and this is manageable. Marsabit-central crop farms are low external-input systems, with negligible use of mineral fertilizer. Eutrophication problem is unlikely due to limited phosphorous inflows through manure while outflows increase with improved crop grains and non-food crop biomass. Additionally, toxicity to crops due to surplus phosphorous has not been reported (Bomans, Fransen et al. 2005).

Ratio of grazing land to crop land: In the wake of climate variability and growing human population, the ratio of grazing land to crop land for provision of manure is gaining attention. Other studies have reported that 14 to 240 ha of rangeland (grazing land) is required to fertilize 1 ha of crop field (Swift, Frost et al. 1989, Vankeulen and Breman 1990, Powell 1994, Powell, Fernandez-Rivera et al. 1996).

This work showed that 11 - 154 ha of grazing land is required to fertilize 1 ha of crop field. The scenario of high forage palatability and 50% collectable manure, under less nutrient uptake by crop, requires lowest area of grazing lands, of about 11 ha of grazing land. However, high yield sole maize production and four-year maize-bean rotations system, under low forage palatability and 30% collectable manure, requires highest area of grazing lands, of about 154 ha.

The grazing lands in Marsabit-central, are already experiencing an expansion of crop agriculture and human settlements. Increasing maize and beans productivity raises the demand on area of grazing land to provide manure. The need to improve crop productivity against the availability of grazing land for farm fertilization requires well considered approach. The ratio of grazing land to crop land need further support of government policy. Undoubtedly, improving the productivity of sole maize production requires more grazing lands for provision of manure. Other production scenarios like sole beans production and two-year 50% land maize and 50% land beans rotation have lower requirement of grazing land. The area of grazing lands required to provide manure fertilizer for crop fields depend on the crop-nutrient uptake, collectable manure and also on the quality of the grazing land. In the Marsabit-central food production systems, grazing land-crop land ratio need to be maintained and measures need to be put in place to avoid putting grazing lands to other uses. For sustainability of crop-livestock agriculture in Marsabit-central farms, extensive and healthy grazing lands is a necessity.

6.8 Limitations and strengths of the method used in scenario analysis

Limitations of the scenario analysis: The calculation of nutrients balance considered only the primary nutrient inputs and primary outputs. There are other potential sources of nutrient inputs and outputs (Figure 5-11).

Also, the collection of manure from distant grazing lands of up to 22 km is a feasible option but it depends on the financial ability and the willingness of the farmers. Alternatively, the farmers also have an option of harvesting forages in the distant grazing lands and transporting to feed livestock in the upper home fields. This can allow close collection of manure.

Why the study considered partial nutrient balance

The primary nutrient inputs, manure and mineral fertilizer, were researched in this study, and the latter was found not being used by the farmers. The primary input (manure) and the primary outputs (crop grains and non-food crop biomass) are farmer-managed and important in crop-livestock production systems. Manure is an important resource in crop-livestock systems of Marsabit-central. It links crop subsystem and livestock subsystem.

Other potential nutrient inputs like wet and dry deposition, biological fixation can likely cancel out with the potential nutrient outputs like erosion, volatilization and leaching. This is evidenced by the following study where closeness of partial and full nutrient balance were found. In the foot slope of Dega, Ethiopia, partial NPK balance (kg/ha/year) of -62, -10 and

-66, respectively, were shown. Also, full NPK balance (kg/ha/year) of -72, -8, and -66, respectively, were reported (Haileslassie, Priess et al. 2007).

Further, leaching is likely minimal in the study area due to uneven amount of rainfall. Consistently, the importance of crop harvests (crop grains and non-food crop biomass) than other nutrient flows like leaching has been reported in SSA (Drechsel, Gyiele et al. 2001).

Therefore, the nutrients in manure, crop grains and nutrients in non-food crop-biomass are the most important fluxes in Marsabit-central food production systems.

Strengths of the scenario analysis

Spatial and temporal variability of forage and manure production is inherent in ASAL areas of Marsabit, northern Kenya. The analysis catered for this variability. Also, the possible crop production scenarios are comprehensively covered under long season and short season yield scenarios.

The scenario analysis considered reduction of forage palatability from 75% in the upper home fields to as low as 43% in the lower grazing lands. Consistently, the NDVI analysis of 2016 and 2017 seasons revealed reduction of NDVI values from upper home fields to lower grazing lands (Figure 3-7).

In addition, the results from scenario analysis are backed by the government reports from crop and livestock departments of Marsabit County, Kenya. Thus, the total area of crop fields in Marsabit-central documented by the government is 1800 ha, and this is comparable with the area of crop fields fertilizable under various scenarios pursued in this work. Consistently, the population of cattle in Marsabit-central sub-county reported by the government is about 60.0 - 80.0 x 10^3 TLUs and this analysis quantified that the cumulative forage biomass in Marsabit-central can support about 69.0 x 10^3 TLUs in median long rain season. The closeness between the findings of this work and the government documentation alludes to the robustness of the scenario analysis.

6.9 Conclusion

Nutrients capture from the grazing lands increase the crop yields and also maintains nitrogen balance. This in the long-term results in sustainable food production systems. Sustainable intensification is currently receiving global attention, and is more conceivable than heightened yields production.

In the fragile environment of Marsabit-central, under long rain season with 50% probability of exceedance, livestock-mediated nitrogen and phosphorous nutrients can sustainably maintain maize grain yields of 2.0 – 4.0 t/ha and bean grain yields of 0.8 - 1.5 t/ha. The nitrogen production in median short rain season can balance nitrogen in only about 1000 ha of crop fields. However, in median long rain season, manure from 22 km grazing distance can balance nitrogen in all 1800 ha of Marsabit-central crop fields. Furthermore, livestock-mediated collectable manure from wetter seasons can balance nitrogen in all 1800 ha of Marsabit-central crop fields and also provides surplus manure-nitrogen to be used in the season of manure limitations.

Nutrient-focused application of manure allows addressing of the most limiting soil nutrient. In this study, field-work phase revealed soil nitrogen as deficient and also showed negative nitrogen balance at field level. Thus, nitrogen-based application of manure solved negative nitrogen balance and this can improve soil nitrogen stock in the long run. Hence, it is plausible to apply manure based on the most limiting nutrient.

Chapter 7 : General discussion and conclusion

7.1 Restatement of the research objectives

The following are the objectives addressed by this study:

- To reveal the main land use classes in Marsabit-central sub-county. The main land use classes are identified and mapped. In addition, Normalized Difference Vegetation Index (NDVI) values are calculated as a measure of land productivity.
- To understand the spatial and temporal variability of rainfall and its influence on production of forage biomass.
- To identify the soil characteristics and crop production practices in Marsabit-central farms. The dominant food crops and nutrient flows within the farmer's crop fields are studied. Additionally, nutrient balance is calculated.
- To explore various options and recommend sustainable food production alternatives. Different scenarios of food production are explored and alternatives for sustainable food production system are suggested.

7.2 Summary of the results

The main land use classes in Marsabit-central Sub-County are: forest, crop fields, good grazing lands and poor grazing lands (Figure 3-2). Crop fields and good grazing lands are mainly concentrated in high altitude areas of 900 to 1300 m asl, and the poor grazing lands are mainly situated in lower altitude zone of 600 to 800 m asl. The land productivity in high altitude crop fields and good grazing lands are higher than the land productivity in low-lying poor grazing lands. This is evidenced by reduction of NDVI values from high altitude areas to lower grazing lands (Figure 3-7). Grazing lands and crop fields are interlinked. Livestock grazes both classes of grazing lands and also on non-food crop biomass from the upper crop fields. Livestock therefore integrates the grazing lands and the crop fields together. Of all the land use classes, crop fields and grazing lands are critical for the survival of humans and livestock population. These land use classes are important for the provision of human foods and livestock feeds. The main factors determining the productivity and the sustainability of crop fields and grazing lands are two twin resources: a) soil nutrients, and b) rainfall.

The rainfall in Marsabit-central varies both with space and time (Figure 4-6). For instance, in the long season of 2016, the difference of rainfall recorded by government meteorological service and site GLKB in grazing lands is 238.3 mm (Table 4-4). Study site GLKB and government meteorological service are about 18 km apart. The rainfall information collected by government meteorological service, in Marsabit town, cannot represent the spatial heterogeneity of rainfall pattern in Marsabit-central sub-county nor in larger Marsabit County. In addition, the interquartile range of 47 years of historical annual rainfall is 373.8 mm (Figure 4-3). Temporally, the rainfall received in the long seasons of 2016 and 2017 were different for all the sites studied. Furthermore, in Marsabit town, there is 10% and 50% exceedance probabilities of receiving 650 mm and 310 mm of long season rainfall, respectively (Figure 4-5). This spatial and temporal heterogeneity of rainfall has implications on the crop and livestock-based livelihoods in Marsabit-central.

The heterogeneity of rainfall results to unevenness in the production of crop and forage biomass. Forage biomass booms in the long season rainfall with utmost 50% probability of exceedance. The median long season rainfall with 50% exceedance probability can produce DM forage biomass ranging from 1511-3500 kg/ha, while the dry long season rainfall with 90% exceedance probability can produce DM forage biomass ranging from 666-1545 kg/ha (Figure 4-16 and Figure 4-20). The lack of consistency in the production of forage biomass affects the number of TLUs that can be fed, thereby influencing the quantity of collectable manure. The collectable manure are important for the provision of soil nutrients.

Whereas phosphorous and potassium are not deficient at the time of study, soil nitrogen limits the food production system in Marsabit-central crop fields. The limitations of soil nitrogen is further exacerbated by prevailing negative nitrogen balance. The measured average nitrogen balance ranged from -41.7 to -66.3 kg/ha/season in the maize fields and -28.8 to -30.2 kg/ha/season in the bean fields (Figure 5-16 and Figure 5-17). Based on the production practices of the year 2016 and 2017, the crop production systems in Marsabit-central is not sustainable. However, livestock-mediated manure can be sustainably used to reverse the nutrient mining.

In the median long rain season, collection of local and distant manure is possible and collectable manure ranges from 5.0-12.0 x 10^6 kg DM, while in the median short rain season, only local manure of about 1.5 x 10^6 kg DM is collectable (Figure 6-5 and Table 6-14). The variability of livestock manure influences the quantity of nutrients received by the crop fields. In the median long rain season, local and distant collection of manure can provide total nitrogen ranging from 103-235 x 10^3 kg, while in the median short rain season, total nitrogen of about 30 x 10^3 kg is available (Figure 6-6 and Table 6-14). Reduction of collectable manure leads to less production of livestock-mediated nutrients in the median short rain season.

In Marsabit-central, livestock manure can be sustainably used to maintain long-term nitrogen balance. This leads to low ranges of positive phosphorous balance, but this is manageable and unlikely to damage the environment. However, utilization of manure increases crop grains and non-food crop biomass resulting in negative potassium balance (Tables 6-16 and 6-17). To reverse negative potassium balance, other potential sources of potassium fertilizer, for example, wood ash and non-palatable forage biomass need further research attention. In spite of negative potassium balance, manure resource can balance the most deficient nitrogen nutrient as well as maintaining the phosphorous balance.

The livestock-mediated nitrogen, phosphorous and potassium are important for crop production, but are affected by the variable environment of Marsabit-central. The variability in rainfall and manure production requires smart production system. Smart production system can be attained by basing the target of the crop yields on the collectable manure. In the long rain season of sufficient manure, high maize grain yields of 2.0 - 4.0 t/ha and high bean grain yields of 0.5 - 1.5 t/ha is achievable. Whilst in the short rain season of manure limitations, maize grain yields of 0.5 - 1.5 t/ha and bean grain yields of 0.4 - 1.0 t/ha is attainable.

Additionally, use of livestock manure by targeting the limiting soil nutrient is the sensible option for improving soil nutrients in Marsabit-central. The sustainability of crop production can be regained by applying equal quantity of nutrient taken out through crop grains and non-food crop biomass back into the crop fields. Therefore, applying manure-nitrogen equivalent to nitrogen offtake by crop grains and non-food crop biomass fosters nitrogen balanced production systems. Additionally, maize-bean rotations also aids in nitrogen fixation. Utilization of livestock manure and maize-bean rotations are available options that can maintain sustainable crop-livestock systems in Marsabit-central.

Therefore, the crop and livestock systems in Marsabit-central can be sustained by optimizing the interaction pathways. Manure plays crucial role in fertilizing crop fields, while also crop fields offer non-food crop biomass as livestock feed. System approaches to the management of crop fields and grazing lands are necessary for maintaining the sustainable food production. The potential for sustainable intensification of Marsabit-central food production system lies in maintaining crop-livestock integration and using livestock manure to reverse the current trend of nutrient mining.

7.3 Contribution of this study to theory

Calculation of Rain Use Efficiency (RUE)

In the food production systems within SSA, limited and variable rainfall reduces potential crop and biomass yields. Little portion of rain put into productive use is also a challenge in rain-fed agricultural systems of SSA. Rain Use Efficiency (RUE) provides information on the portion of rainfall put into productive use (Sileshi, Akinnifesi et al. 2011). Based on the status of RUE, measures to put more rain to productive use can be implemented. Low RUE is an opportunity to improve productivity of rainfall. While previous studies, largely considered, RUE for crop grain yields, this work calculated both RUE for crop grain yields and RUE for total aboveground biomass. Total aboveground biomass is inclusive of crop grain yields and non-food crop biomass. Non-food crop biomass is an important source of livestock feed in crop-livestock systems. The RUE for total aboveground biomass shows total portion of rain put in to productive use. Therefore, RUE for total aboveground biomass is recommended in a similar crop-livestock production systems.

Modelling nutrient balance

Nutrient balance is an important indicator of sustainability in agricultural systems. Nutrient balance is calculated at different levels including crop level, animal, field, farm, district, sub-national, national, continental and at global levels. In SSA, the studies on nutrient balance is complicated by the complexity of food production systems. The nutrient balance in SSA involves nutrient flows between the crop fields, livestock and extensive grazing lands.

The previous nutrient modelling work in SSA mainly used coarse national-level data (Drechsel, Gyiele et al. 2001). Although some progress has been made in modelling nutrient balance, the following are the key limitations of the previous modelling studies calculating nutrient balance in SSA:

I. Land use classes generalized either as exclusively for crop fields or as for livestock production. Some modelling work used global crop land data, which lacks spatial resolution (Jägermeyr, Gerten et al. 2016) (Nol, Verburg et al. 2008). The assumption on general land use class is made due to scarcity of spatial data. The area of arable lands within mountain and oasis parts of ASALs end up being regarded as exclusive livestock grazing zone. The decision made on the type of land use class has an influence on the calculation and result of nutrient balance. Furthermore, assuming land use class as either solely crop fields or grazing lands ignore the interconnectedness within small-holder crop-livestock and grazing land systems of SSA.

II. Previous work estimated area of hectares used by livestock for grazing and hardly considers the variability of forage production (Herrero, Grace et al. 2013). The forage biomass in SSA booms in seasons of better rainfall and reduces in seasons of short rain or in seasons of drought. The palatability and the availability of forage biomass also changes with space. Livestock opportunistically moves in extensive grazing lands to utilize this variable forage biomass. This variability affects the grazing itinerary and the spatial distribution of livestock.

III. The estimates for livestock population size are approximate, and does not incorporate seasonal changes (Kruska, Reid et al. 2003, Robinson, Wint et al. 2014). The grazing location of livestock population in ASALs follows the seasonality of forage production. High number of livestock are found where there is extensive grazing lands with sufficient forage biomass.

IV. Earlier modelling studies rarely separates between produced manure and the quantity of manure available for fertilization of crop fields. In some case, assumption is made on the total utilization of produced manure (Nandwa and Bekunda 1998).

V. The distances between crop fields and grazing lands affect the collectability of livestock manure. In some season, livestock move further away from crop fields, and some manure may not be accessible. In SSA, there is no study on nutrient modelling found, considering distances between crop lands and grazing lands.

This study addressed the aforementioned limitations in the following ways:

This work has confirmed that GIS and remote sensing applications can reveal various land use classes in the area of interest. Knowing distinct land use classes allow for identifying potential nutrient inflows and outflows in each and every land use classes. This enables quantification of the relevant nutrient flows in each land use classes. Furthermore, different land use classes in specific geographical region permits for consideration of nutrients flowing between the land use classes. In this study, crop fields and grazing lands are two distinct land use classes and nutrient flows between them were quantified. Therefore, GIS application tools complement the modelling of nutrient balance, especially in remote and data-scarce areas of SSA.

Forage variability has been addressed in the modelling work of this study. This study has demonstrated that palatable forage biomass is found on high altitude areas while palatability reduces as moving into low-lying grazing lands. The spatial variability of forage biomass ranges from 75-43%. 75% palatability is in good grazing lands on high altitude areas and 43% palatability is in poor grazing lands within the lowlands. This is also confirmed by remote sensing chapter of this work (Chapter 3), where better NDVI was found in high altitude areas (Figure 3-7). In modelling of nutrient balance, it is important to recognize that palatability of forage biomass changes with landscape. Temporally, this study has shown that forage biomass is sufficient for TLUs in long rain season with 50% exceedance probability. However, short rain season and drought sometimes reduce the quantity of forage biomass. This forage variability results to changes in grazing itinerary and sometimes livestock moves to distant grazing lands, further away from crop fields. This occasional movement of livestock to further distance weakens the mutual benefits within small-holder crop-livestock systems. Nutrient modelling in SSA need to reflect the spatio-temporal variability of forage production.

In addition, livestock population has been an area of uncertainty in modelling nutrient balance, within SSA (Robinson, Wint et al. 2014). In some case, FAO data on livestock numbers is used, which lacks spatial and temporal resolution. The variability of livestock population can be identified from seasonal changes in forage production. Livestock grazes where there is rainfall that can produce ample forage biomass. The population of livestock can be estimated by dividing DM cumulative forage biomass by daily DM forage intake of TLU within specified duration of time. This results in livestock population that can be fed within specified season. The livestock population is further validated with district-level statistic and by household interviews. This work modelled the nutrient balance taking into account the changeability of livestock population that can provide manure.

The quantity of manure produced and the collectable manure for fertilization of crop fields was fully represented in this study. In SSA, the mobility of livestock and the logistics of manure collection cannot allow use of 100% of produced manure. This is owing to occasional movement of some livestock to far away distance from crop fields to graze in better grazing lands and also possibility of lacking the means of collecting manure. This analysis has used different portions of collectable manure. The collectable manure ranges from 50-30% of produced manure. 50% represents a case where livestock graze in grazing lands and spend 12 hours of night at home *boma*. All the manure dropped in *boma* at night is collected and used in crop fields. The 30% case is collection of distant manure when all night manure is not collectable. It is important in modelling of nutrient balance to cater for the differences in the produced manure and the collectable manure.

In this work, the maximum distance into the grazing lands where manure is collectable is 22 km. This is based on the logistics of transporting manure and the cost of manure collection. Above a 22 km distance from the upper crop fields in to the grazing lands, manure collection is not economically viable. Also, in median short rain season, the possible distance of manure collection is up to within 7 km grazing distance from crop fields. The 7 km grazing distance is based on some livestock moving to inaccessible grazing lands in times of pasture scarcity.

Moreover, nutrient modelling should initially start with the identification of the potential nutrient inputs and outputs in the area of interest. Nutrient modelling of this work started with identifying and mapping the potential nutrient flows in Marsabit-central. Nutrient-flows not found in previous studies, this work revealed that wood ash and house maintaining materials are potential nutrient flows in Marsabit-central and also in similar ASAL areas of SSA (Figure 5-11). Therefore, initial identification and mapping exercise can reveal site-specific nutrient flows in the area of interest.

Finally, system analysis enables in-depth research on integrated crop-livestock production. However, the isolated studies on crop performance or only on livestock production cannot comprehensively reveal the interlinkages within the integrated production systems. Further, isolated work may fail to recognize the benefits that may be harboured in integrated crop-livestock systems. Integrated crop-livestock systems has potential for sustainable intensification which is currently on global policy agenda. Therefore, it is sensible to use system approaches to explore the intensification pathways within the integrated crop-livestock systems.

7.4 Contribution of this study to policy

The field-work phase and the land use classification have distinguished between good and poor grazing lands in Marsabit-central. The poor grazing lands are characterized by shrubs, bareness, and stoniness in addition to grass pasture. Efforts toward reducing the shrubs, stones and bareness can promote restoration of poor grazing lands to good grazing lands. Government policy on management and reseeding of grazing lands can improve poor grazing lands while also maintaining the health of good grazing lands.

Additionally, to address continuous nutrient mining from food production systems of SSA, a policy on nutrient management is necessary. A policy that constitutes regular calculation of field-level nutrient balance can maintain sustainable production system in Marsabit-central and other similar parts of Kenya. Nutrient balance policy can guide in identifying the nutrient needs of a production systems. This can inform the farmers, government and other stakeholders on the essential interventions to address food production and environmental quality.

Crop fields and grazing lands are two interdependent land use classes. Livestock links crop fields and grazing lands together, and also livestock acts as a vector of manure. Grazing lands produce livestock manure that can provide nutrients for crop fields, and therefore necessary for sustainable food production.

This study has demonstrated that different scenarios of maize and beans production requires different quantity of livestock-mediated manure. Therefore, high maize yields of 4.0 t/ha requires more quantity of manure than low maize yields of 1.0 t/ha. Similarly, high bean yields of 1.5 t/ha requires more quantity of manure than bean yields of 0.4 t/ha. Thus, different scenarios of maize and beans production also need different hectares of grazing lands for provision of manure.

Sole beans production requires the lowest hectares of grazing land while sole maize production demands the highest hectares of grazing land to provide manure. Other scenarios like two-year, three-year and four-year maize-bean rotations require intermediate hectares of grazing lands for provision of manure. One ha of sole beans production requires 11-73 ha of grazing land to provide manure under balanced nitrogen. However, one ha of sole maize production requires 18-154 ha of grazing land for manure provision, under balanced nitrogen.

The total area of crop fields in Marsabit-central is estimated at 1800 ha. Therefore, 19.8 - 277.0 x 10^3 ha of grazing lands is required to provide manure for all 1800 ha crop fields in Marsabit-central Sub-County, under balanced nitrogen fertilization. Sustainable food production in Marsabit-central needs grazing land-crop land ratio to be maintained.

It is possible for other human activities to reduce the extent of grazing lands. These include: increase in settlements with human population growth. The field-work phase of this study has found human settlements picking up in the grazing lands. Similarly, other land use activities like expansion of crop fields and industries can utilize the grazing lands at the expense of livestock production.

However, for sustainability of crop-livestock systems, it is necessary to maintain required hectares of grazing land to support crop fields with livestock-mediated manure. Therefore, a government policy to save 277.0 x 10^3 ha of land for livestock grazing is recommended. Crop-livestock integration systems in Marsabit-central need to be supported with government policy.

7.5 Contribution of this study to practice

Small-holder farming systems in SSA is challenged by low soil fertility (Sanchez 2002). This requires continuous monitoring of the production systems. Sustainability indicators are decision making tool and guides in maintaining productive and healthy agro-ecosystem. It provides basis for making decision on the quantity of manure input. The quantity of manure to be applied to the crop fields can be known from sustainability indicator. In Marsabit-central farms, the limiting soil nitrogen and negative nitrogen balance requires closer attention. Therefore, nitrogen concentration in the soils and the nitrogen balance of crop field are recommended sustainability indicators for Marsabit-central food production systems.

Additionally, the existence of both crop fields and livestock unit at farm, village or sub-county level offers opportunity for sustainable food production. It provides manure for fertilization of crop fields. In SSA, the subsistence rain-fed system has been experiencing low crop yields (Nyagumbo and Bationo 2011). Livestock-mediated manure can be used to improve the current crop yields production in Marsabit-central and similar environment. Manure can sustainably increase the maize grain yields which currently oscillates around 1.1 t/ha in Marsabit-central, up to 2.0-4.0 t/ha. Similarly, manure can also improve bean grain yields from current average of 0.7 t/ha to 0.8-1.5 t/ha.

The spatio-temporal variability in rain and forage biomass influences the grazing itinerary of livestock, and thereby the quantity of collectable manure. This variable environment requires smart use of manure resources. The fertilizer value of manure can be optimized by aligning crop yields target to the quantity of collectable manure. In the season with possibility of collecting manure from local and distant grazing lands, maize grain yields ranging from 2.0-4.0 t/ha and bean grain yields of 0.5-1.5 t/ha can be targeted. However, in short rain season with only possibility of collecting local manure, maize grain yields of 0.5-1.5 t/ha and bean grain yields ranging from 0.4-1.0 t/ha are attainable.

Also, using the collectable manure to balance the most limiting soil nutrient fosters sustainable food production. Nitrogen is the limiting nutrient in the crop fields of Marsabit-central. Applying livestock-mediated nitrogen to the crop fields equivalent to the quantity of nitrogen offtake by crop grains and non-food crop biomass results in balanced nitrogen, and maintains sustainable production system. This is a worthy effort in line with sustainable crop-livestock integration.

7.6 Future research areas

With the aim of furthering research and based on this work, the following research areas are suggested:

Rain Use Efficiency (RUE) is important in disclosing the portion of rainfall used for beneficial transpiration. In this work, under farmer's practices, the average maize grains yield RUE oscillates around 2.37-2.97 kg/ha/mm and the average bean grains yield RUE ranges from 1.54-2.23 kg/ha/mm. These RUE of crop yields are generally low, and manure treatment in this study improved RUE. Also, previous studies have shown that measures such as rainwater harvesting, mulching and water conservation practices can improve RUE (Oweis and Hachum 2006, Dile, Karlberg et al. 2013). It is recommended to do further research on synergistic benefits of rain and soil management practices that may make rain more productive, while also increasing crop yields in ASAL areas.

Also, this work showed that increasing crop productivity while at the same time balancing nitrogen, results in negative potassium balance. Therefore, further research efforts geared at balancing nitrogen, phosphorous and potassium simultaneously is necessary.

In addition, as the African famers strive to increase crop yields, the potassium offtake in crop grains and non-food crop biomass can increase and this will likely result in negative potassium balance. A research on alternative sources of potassium fertilizer for African agriculture is required. For example, some silicate rock sources and non-palatable pasture in the grazing lands may be source of potassium fertilizer.

Whilst this study has considered the primary nutrient inputs and primary nutrient outputs for calculation of nutrient balance, other potential nutrient inflows and outflows have also been identified. For example, nutrient outflows through materials used for maintaining houses (Figure 5-11). It is worth including these additional identified nutrient flows in the calculation of nutrient balance. This can reveal if there is significant difference between nutrient balance revealed in this work and calculation of nutrient balance with addition of other nutrient flows.

Furthermore, crop-livestock integration has potential for multiple economic and environmental benefits. This study showed economic benefits of manure by improving crop yields. Also, balancing of nitrogen by use of livestock-mediated manure is sustainable and also beneficial to the environment. It is valuable to quantify other potential benefits of crop-livestock systems in Marsabit-central or similar ASAL environment.

Finally, a study on grazing management practices, for example, establishments of exclusion zones to facilitate regeneration, is necessary. This is to find the best method that can improve poor grazing lands as well as maintaining the health of good grazing lands.

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A Appendix

Appendix 1: Rainfall recording sheet

Location: …………………………………………………………….

Farmer's Name: ………………………………………………….

GPS Points: ……………………………………………………….

Year: ……………………………………………………………….

Month: …………………………………………………………….

Date	Day	Number of hours it rained	Rainfall (mm)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

Appendix 1: Rainfall recording sheet ……Continued

Date	Day	Number of hours it rained	Rainfall (mm)
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
31			

Appendix 2: Rainfall data in study area for the long seasons of year 2016 and 2017

SG LOCATION						DK LOCATION					GRAZING LAND (GL)					METEREOLOGICAL DATA (Gov't Met)			
Months	Farms	Amount of rain per month (mm) 2016	Number of days it rain in the month of 2016	Amount of rain per month (mm) 2017	Number of days it rain in the month 2017	Farms	Amount of rain per month (mm) 2016	Number of days it rain in the month 2016	Amount of rain per month (mm) 2017	Number of days it rain in the month 2017	Sites	Amount of rain in each month (mm) 2016	Number of days it rain in the month 2016	Amount of rain in each month (mm) 2017	Number of days it rain in the month 2017	Amount of rain in each month (mm) 2016	Number of days it rain in the month 2016	Amount of rain in each month (mm) 2017	Number of days it rain in the month 2017
April	JD	390.1	15	144.2	9	ED	430.5	16	106.3	12	SK	376.9	13	35	9	526.7	17	76.2	11
May	JD	86.9	5	155	9	ED	119.1	5	49	10	SK	33.5	5	48	7	61.5	4	55.8	9
June	JD	5	1	0	0	ED	14.5	7	0	0	SK	0	0	0	0	9	5	0	0
July	JD	3	1	0	0	ED	0.5	1	0	0	SK	0	0	0	0	1	1	6.4	1
August	JD	3	1	0	0	ED	1	2	0	0	SK	0.5	1	0	0	0	0	13.3	4
Total		**488**	**23**	**299.2**	**18**		**565.6**	**31**	**155.3**	**22**		**410.9**	**19**	**83**	**16**	**598.2**	**27**	**151.7**	**25**

Appendix 2 ………. Continued

SG LOCATION						DK LOCATION					GRAZING LAND (GL)							
Months	**Farms**	**Amount of rain per month (mm) 2016**	**Number of days it rain in the month of 2016**	**Amount of rain per month (mm) 2017**	**Number of days it rain in the month 2017**	**Farms**	**Amount of rain per month (mm) 2016**	**Number of days it rain in the month 2016**	**Amount of rain per month (mm) 2017**	**Number of days it rain in the month 2017**	**Sites**	**Amount of rain in each month (mm) 2016**	**Number of days it rain in the month 2016**	**Amount of rain in each month (mm) 2017**	**Number of days it rain in the month 2017**	**BD location (months)**	**Amount of rain (mm) 2017**	**Number of days it rained**
April	JL	387.4	14	185	12	JG	449.9	15	97.6	8	KB	327.9	10	58.5	6	**Months**		
May	JL	103.5	5	193	10	JG	112.6	5	52	12	KB	31.5	2	37	5	April	140.4	11
June	JL	5	1	0	0	JG	8	2	0	0	KB	0	0	0	0	May	126.9	11
July	JL	3	1	0	0	JG	0.5	1	0	0	KB	0	0	0	0	June	0	0
August	JL	3	1	0	0	JG	1	1	0	0	KB	0.5	1	0	0	July	0	0
Total		**501.9**	**22**	**378**	**22**		**572**	**24**	**149.6**	**20**		**359.9**	**13**	**95.5**	**11**	August	0	0
April	LK	365.9	13	156.3	12	MK	385.9	16	116.8	11	KQ	329.9	10	46.4	3	**Total**	**267.3**	**22**
May	LK	69.5	5	156	10	MK	141	5	42	8	KQ	35	3	23.5	5			
June	LK	5	1	0	0	MK	12.3	6	0	0	KQ	0	0	0	0			
July	LK	3	1	0	0	MK	0.5	1	0	0	KQ	0	0	0	0			
August	LK	3	1	0	0	MK	1.5	2	0	0	KQ	0	0	0	0			
Total		**446.4**	**21**	**312.3**	**22**		**541.2**	**30**	**158.8**	**19**	**KQ**	**364.9**	**13**	**69.9**	**8**			

Appendix 3: Questionnaire used for data collection

Farmers pursuing both crop and livestock production (mixed crop-livestock system); these involve farmers who own both at least one acre of crop field and at least 3 TLUs (livestock) i.e. zebu cattle. Their livestock is utilizing communal grazing land during wet seasons, and home field (crop residues and pasture in home fields) during dry season. This is the dominant food production practices in the study area.

Question 1; Socio-economic characteristics of farming communities

1.1 How many people are living in your house? ………………………….

1.2 Please give their age structure?

Up to 0 to 6 years …………… Up to 7 to 12 years ………………… Up to 13 to 18 years…………………………. Above 18 years ………………….

1.3 Does the household use latrines or open fields (the researcher looks whether there is latrine outside and answer this question) (1) yes (2) No

Capturing nutrient lost in fuel wood

Kilogram of Ash produced by household		
Month 1	Month 2	Month 3

Question 2; to capture crop information.

2.1 What is the size of your total land under crop production (in acres)?

…………………………………

2.2 Which crop variety (maize, beans, khat, vegetables, other legumes e.g peas, green grams) are you growing and for each on what size of land in the current season? Give also yield per growing season? What quantity of crop residues are produced from each crop type?

	Crop variety e.g. maize, beans, Khat, other legumes like peas, green grams	Size of land under each crop (acres)	Yield in Kg per season (3-5 months)	Local market value of yield per kg (Kenya shillings)	Seasonal income per season (Kenya shillings)	Estimated weight of crop residues produced (kg)	Market value of crop residues per kg (Kenya shillings) per season	Since when have you started producing/farming this crop (Just write year the farmer started)
1	Maize							
2	Beans							
3	Khat							
4								

Of the maize and beans produced, what kilogram are used for household consumption? Amount for gift? and what kilogram are sold?

	Total produced in kg per season	Kilogram used for Household consumption per season	Kilogram of gift per season	Kilograms sold per season
Maize				
Beans				

2.2.1 Which is the main month of the year are you carrying out the following activities? (Labour partitioning)

Activities	Crop	Month (s) of the year											
		Jan-1	Feb-2	Mar-3	Apr-4	May-5	Jun-6	Jul-7	Aug-8	Sep-9	Oct-10	Nov-11	Dec-12
Land preparation	Maize												
	Beans												
	Khat												
	Other crop												
Sowing/ planting	Maize												
	Beans												
	Khat												

2.2.1 Which is the main month of the year are you carrying out the following activities? (Labour partitioning) ……….. Continued

Activities	Crop	Month (s) of the year											
		Jan-1	Feb-2	Mar-3	Apr-4	May-5	Jun-6	Jul-7	Aug-8	Sep-9	Oct-10	Nov-11	Dec-12
Weeding	Maize												
	Bean												
	Khat												
	Other crop												
Harvesting	Maize												
	Bean												
	Khat												
	Other crop												
Herding													
Migrating with animals													

2.3 Use of crop residues

Use of crop residues	Yes =1 No=0	1-Used all for this purpose=100%, 2-Used half (1/2) & Quarter (1/4) for this purpose=75% 3-Use half (*Nusu*) for this purpose=50% 4-Used quarter(1/4) for this purpose=25%
Feeding cattle		
Feeding small stock		
Feeding Camel		
Feeding donkey		
Used for fertilizing crop field		
Burning		
Selling		
No planned use		
Other, specify		

2.4 Source of labour for crop production

Crop variety e.g. maize, beans, khat, other legumes like peas, green grams.	Labour for land preparation			Labour for planting/sowing			Labour for weeding			Labour for harvesting			Cost of other inputs, if any, per season (KES)
	Who provides labour for land preparation (owner-1 Hired-2)	Cost per day (KES)	No. of Land p days	Who provides labour for planting (owner -1 Hired-2)	Cost of hiring per day (KES)	Number of planting days	Who provides labour for weeding (owner-1 Hired-2)	Cost of weeding per day (KES)	No. of weeding days	Who provides labour for harvesting (owner-1 Hired-2)	Cost of harvesting per day (KES)	No. of harvesting days	
Maize													
Beans													
Khat													

2.5 Pests and diseases affecting main crops

Crops (Maize, Beans, Khat, other crops)	Pests and diseases				
	Local name of pest or disease	Scientific Name of pest or disease	Chemical use or non-use to control (1-use chemical, 2-No use of chemicals	Name of main chemical used to control specific pest or disease	Amount of money used to control specific pest/disease per season (KES)
Maize stalk borer					
Maize pest 2					
Maize pest 3					

2.5 Pests and diseases affecting main crops ……………Continued

Crops (Maize, Beans, Khat, other crops)	Pests and diseases				
	Local name of pest or disease	Scientific Name of pest or disease	Chemical use or non-use to control (1-use chemical, 2-No use of chemicals	Name of main chemical used to control specific pest or disease	Amount of money used to control specific pest/disease per season (KES)
Bean pest 1					
Bean pest 2					
Bean pest 3					
Khat pest 1					
Khat pest 2					

2.5 Pests and diseases affecting main crops ……………Continued

Crops (Maize, Beans, Khat, other crops)	Pests and diseases				
	Local name of pest or disease	Scientific name of pest or disease	Chemical use or non-use to control (1-use chemical, 2-No use of chemicals	Name of main chemical used to control specific pest or disease	Amount of money used to control specific pest/disease per season (KES)
Khat pest 3					
Maize disease 1					
Maize disease 2					

2.5 Pests and diseases affecting main crops ……………Continued

Crops (Maize, Beans, Khat, other crops)	Pests and diseases				
	Local name of pest or disease	Scientific name of pest or disease	Chemical use or non-use to control (1-use chemical, 2-No use of chemicals	Name of main chemical used to control specific pest or disease	Amount of money used to control specific pest/disease per season (KES)
Maize disease 3					
Bean disease 1					
Bean disease 2					
Bean disease 3					

2.6 Mineral and manure fertilization of crop field

Crop	Fertilizer used =1 Fertilizer not used =0					Manure		
		Name of fertilizer used	kilogram or litre of fertilizer used per ha per season	Unit cost of fertilizer-KES/kg	Total cost of fertilizer season-KES	Manure used -1 Manure not used -0	Kilogram/wheelbarrow of manure used on each crop field per ha per season	Equivalent monetary value (KES)
Maize								
Beans								

2.6 Mineral and manure fertilization of crop field ……………..Continued

Crop	Fertilizer used =1 Fertilizer not used =0					Manure		
		Name of fertilizer used	kilogram or litre of fertilizer used per season	Unit cost of fertilizer-KES/kg	Total cost of fertilizer season-KES	Manure used -1 Manure not used -0	Kilogram/wheelbarrow of manure used on each crop field per ha per season	Equivalent monetary value (KES)
Khat								
Other crop								

2.7 What size of your home field have not been under crop production (acres)? ……………………..

2.8 What is the main reason of not cultivating the mentioned size of land? (1) Kept aside for grazing home based livestock (2)Kept aside for animals during dry season when they are back from communal grazing lands (3) No resources (labour, farm power) to cultivate (4) Other reason (s), specify ………….

Question 2.8 table

Reason (s) for not cultivating some part of home field			
Kept aside for grazing home based livestock yes-1, No-0	Kept aside for animals during dry season when they are back from communal grazing lands Yes-1, No-0	No resources Yes-1 No-0	Other reasons, Specify

Question 3: to capture livestock information

3.1 Tell us the livestock species you own, number of each livestock and use for each species

Livestock species e.g cattle, small stock (sheep and goat), camels, donkey	**Number of each livestock species your own**			**Main use; 1-milk, 2-cash 3-farm power 4-other, specify**	**If main use is milk, what is the daily milk yield per animal from each livestock species (litres)**	**Number of animals in milk**	**Lactation period (month it continue giving milk to the family?**	**Local market value of milk per litre (KES)**	**If main use is cash, give total annual income from each livestock species (KES)**	**Number of mature animal sold in previous year**	**Local market value of matured animal (KES) average of male and female price**	**Number of hides/skin produced in the last 3 months**	**Local market value of single hide or skin (KES)**
	Matured male	Matured female	≤1.5 years										
Cattle													
Goat													
Sheep													
Camel													

3.2 Use of livestock for farm related power – ploughing, watering, transporting farm products etc

Livestock species used for power e.g cattle (oxen), camels, donkeys	Is this animal used for power provision yes-1 No-0	Type of power e.g. 1-ploughing, 2-fetching water for small animals and human use 3-Transporting farm produce	Number of each livestock species providing power	Number of days per season (3 months) work/power is provided	Market value of power provision per day e.g (cost of ploughing by oxen per day) – KES
Uses of cattle –Oxen					
Uses of camel					
Uses of Donkey					

3.3 Source of labour for livestock production

Livestock species e.g cattle, small stock (sheep and goat), camels	Number of each livestock species your own	Who provides Labour for herding animals (1-Owner or 2-Hired)	If hired, what is the monthly cost of herding (KES)	Who provides Labour for watering animals (1-owner, 2-hired)	If hired, what is the monthly cost of watering (KES)
Cattle					
Goats					
Sheep					
Camel					

Question 4; to capture manure production

4.1 Please tell us the months when you animals are grazing in the home field and when they are grazing in communal grazing lands?

Months of the year	Cattle		Small stock	
	Home/crop field	Communal Grazing land	Home/crop field	Communal grazing land
January				
February				
March				
April				
May				
June				
July				
August				
September				
October				
November				
December				

4.2 What number of wheelbarrows (one wheelbarrow of manure weighs 46kg) of manure do you produce per month from each livestock species when animals are at home field? …………………………….

Livestock species	Amount of manure produced per month (wheelbarrows)
Cattle manure	
Small stock manure	
Camel manure	

4.2.1 What is the mineral fertilizer equivalent monetary value of monthly manure produced by the farmer? What does 1kg of compound fertilizer cost (N, P. K)? (look for this in the local market)…… ……………KES Equivalent monetary value of manure produced……………… KES NB. This is done after nutrient analysis.

4.3 What duration of time do you stay before removing manure from kraal (if for example you remove today, after how many days will you remove again)?.. days

4.4 What do you do with animal manure? (1) Directly broadcast manure after removal in crop fields for fertilization, (2) Heaped together outside, (3) Just thrown away for no planned use (4) Other, specify

4.5 If manure is heaped outside, will you use it for fertilization during cropping season? (1) Yes (2) No

4.6 If yes, how long does manure stays in heaps before used for farm fertilization? …………….

Question 4.4 to 4.6

	Is manure broadcasted directly in crop field Yes – 1 No-0	Does manure collected from kraal & heaped outside Yes-1 No-0	Does manure heaped outside used for farm fertilization Yes-1 No-0	For how many/months days does manure stay in heaps before used for fertilization	Is manure just thrown away without any plan of use Yes-1 No-0
Cattle manure					
Small stock manure					
Camel manure					

4.7 What is the size of your *boma* (where animals sleep at night) in M^2? This question is not asked but the diameter of the kraal will be measured by the researcher and the area is calculated. Kraal is normally circular in shape.

…………………………………..M^2.

4.8 How many days does manure stays in kraal before it is removed? ……………………… days

Question 4.7 and 4.8 table

	Size of kraal (m^2)	Number of days manure stays in kraal before removal
Cattle kraal		
Small stock kraal		
Camel kraal		

Question 5; to capture nutrient lost in maintaining houses

5.1 Do you plaster your house (floors & walls) using mixture of soil and manure? (1) Yes (2) No

5.2 If yes, how many times per month? …………………………

5.3 What size (kilogram) of mixture do you use each plastering time? ……………….. Kg

5.4 What size (kg) of soil do you use in mixture ………………….. kg

5.5 What size of manure (kg) do you use in the mixture ………………. kg

The researcher also measures size of mixture and records …………………………… kg

5.6 Calculating area of the walls and area of the floor (the total plastered area); the researcher measures and calculate area of floors and perimeter of wall

………………………………………. M

Do you regularly plaster your house Yes-1 No-0	Do you use topsoil when plastering house Yes-1 No-0	Do you use manure when plastering house Yes-1 No-0	What is the source of manure used for plastering your house (1-cattle, 2-small stock, 3-camel, 4-donkey, 5-chicken)	How many times per month do you plaster your house	What is the normal total weight of plaster mixture (kg)	What is the weight of top soil in the mixture in (kg)	What is the weight of manure in the mixture-kg)	What is the total area of your house plastered regularly – m^2

The researcher collects samples of mixture (soil and manure) for laboratory analysis.

Appendix 4: Maize and beans laboratory results for 2016 long season

	Maize grain		Maize non-food biomass		Bean grain		Bean non-food biomass	
Location	N%	C%	N%	C%	N%	C%	N%	C%
DK	1.40	41.80	0.60	37.80	2.80	39.80	0.70	41.50
DK	1.40	45.00	0.60	40.60	2.60	37.90	0.70	42.20
DK	0.60	44.80	0.60	41.90	2.80	41.10	0.70	42.10
DK	1.00	42.00	0.60	38.70	3.30	41.10	1.10	40.70
DK	1.00	43.00	0.60	40.00	3.10	40.60	0.80	40.60
DK	0.60	42.10	0.60	40.30	3.00	40.00	0.80	41.60
DK	1.10	40.50	0.50	42.50	2.80	38.60	0.70	41.20
DK	1.10	41.50	0.50	42.70	2.70	39.00	0.70	42.80
DK	0.70	41.80	0.60	40.60	2.60	39.60	0.80	43.50
SA	1.40	42.30	0.60	38.60	3.00	42.50	0.90	41.70
SA	1.30	42.40	0.60	38.30	2.90	42.90	1.00	41.90
SA	1.40	41.70	0.60	39.80	2.90	41.00	0.80	42.50
SA	1.30	44.10	0.60	40.50	2.90	40.70	0.80	41.80
SA	1.30	44.60	0.50	40.60	2.70	39.00	0.80	41.30
SA	1.20	42.80	0.50	41.20	2.50	39.40	0.80	40.90
SA	1.20	42.20	0.60	41.40	2.50	40.60	1.00	41.20
SA	1.30	45.00	0.60	41.30	2.40	39.60	1.00	41.10
SA	1.20	42.40	0.60	40.80	2.70	42.20	0.90	40.80
BD	1.30	41.90	0.90	43.40	3.30	42.20	2.00	42.80
BD	1.30	41.60	0.80	43.00	3.30	43.40	0.70	42.10
BD	0.50	43.80	0.70	42.70	3.30	42.50	0.70	42.20
BD	1.30	42.10	0.70	38.50	3.00	42.10	2.50	42.00
BD	1.30	41.90	0.70	40.40	3.00	40.90	1.10	41.70
BD	1.30	42.80	0.60	39.90	3.00	41.20	1.10	41.60
BD	1.30	44.40	0.50	43.20	3.30	41.10	1.00	41.80
BD	1.30	45.10	0.60	43.10	3.30	43.60	1.00	42.10
BD	1.20	41.40	1.30	43.00	3.40	42.40	0.90	40.90
SG	1.30	42.40	0.70	42.50	2.70	42.90	1.20	41.30
SG	1.30	40.80	0.60	42.90	2.80	41.20	0.80	41.40
SG	1.20	40.20	0.90	42.00	2.80	42.30	0.80	40.80
SG	1.20	42.50	0.70	40.60	3.40	41.70	1.50	41.30
SG	1.20	42.90	0.80	40.60	3.40	42.70	1.40	41.40
SG	1.20	43.60	1.10	42.40	3.50	43.10	1.00	40.30
SG	1.30	41.80	0.60	44.40	3.20	41.60	1.20	41.30
SG	1.30	41.60	0.50	42.60	3.20	40.30	0.80	41.80
SG	1.30	43.10	1.30	42.60	3.20	42.00	0.80	42.70

Appendix 5: Maize and beans laboratory results for 2017 long season

Location	Maize grain		Location	Maize non-food biomass		Location	Bean grain		Location	Bean non-food biomass	
	N%	C%		N%	C%		N%	C%		N%	C%
SG	1.60	41.20	DK	2.33	41.90	DK	4.50	39.30	DK	4.00	41.60
SG	1.30	42.60	DK	2.01	42.40	DK	5.10	38.40	DK	2.30	43.70
SG	1.60	40.50	DK	2.23	38.40	DK	4.50	38.80	DK	2.50	41.70
SG	1.60	41.70	DK	2.64	36.40	DK	4.50	39.00	DK	1.80	40.10
SG	1.40	41.20	DK	2.41	38.30	DK	4.60	40.30	DK	3.30	39.40
SG	1.60	40.30	DK	1.68	39.50	BD	3.90	40.10	DK	4.00	46.40
SG	2.00	46.40	DK	1.79	40.90	BD	3.60	39.30	DK	1.70	39.60
SG	1.60	40.60	DK	1.46	37.80	BD	4.00	37.90	DK	3.40	39.80
SG	1.70	41.30	DK	1.61	38.80	BD	4.20	41.60	DK	2.80	45.00
SG	1.70	40.70	DK	2.11	43.10	BD	4.00	39.10	DK	2.40	44.30
SG	1.90	41.60	DK	2.06	39.40	BD	4.20	40.90	DK	2.50	39.90
SG	1.60	42.60	DK	1.97	39.90	BD	3.90	41.00	DK	2.20	39.90
SG	1.80	46.30	BD	2.68	39.80	BD	3.90	41.50	DK	2.60	40.10
SG	1.50	39.90	BD	3.84	38.40	BD	4.70	38.60	DK	4.90	38.40
SG	1.50	40.10	BD	1.00	47.20	BD	4.40	41.00	DK	4.50	39.80
SG	1.60	39.80	BD	0.79	42.80	BD	4.20	37.00	DK	3.30	42.20
SG	1.50	41.30	BD	0.60	45.70	BD	5.20	39.80	DK	1.80	40.30
SG	1.90	41.30	BD	1.34	45.20	BD	3.80	42.90	DK	2.20	40.00
SG	1.80	40.70	BD	0.59	45.30	BD	3.60	40.30	DK	1.80	44.50
SG	1.80	40.60	BD	0.76	42.00	BD	3.90	42.10	DK	2.20	44.70
BD	1.50	41.10	BD	0.63	41.10	BD	3.70	40.40	DK	1.30	39.90
BD	1.50	40.70	BD	0.54	43.20	BD	3.70	40.70	DK	1.90	42.80
BD	1.60	41.90	BD	0.84	40.40	BD	4.90	39.60	BD	1.00	45.50
BD	1.60	40.10	BD	1.02	45.30	BD	4.00	40.20	BD	1.10	45.90
BD	1.60	40.60	SA	1.68	41.70	BD	3.90	38.50	BD	0.90	40.50
BD	1.80	40.90	SA	1.79	38.30	BD	3.90	40.40	BD	3.60	39.90
BD	1.50	40.50	SA	1.46	44.20	BD	4.00	40.40	BD	2.50	43.90
BD	1.80	41.50	SA	1.61	44.50	BD	4.00	39.00	BD	1.90	41.10
BD	1.80	44.60	SG	2.97	40.20	BD	4.20	38.00	BD	1.70	39.40
BD	1.70	38.80	SG	2.91	46.50	SG	4.50	40.00	BD	1.50	39.90
BD	1.60	41.00	SG	1.70	45.30	SG	5.20	41.20	BD	1.70	39.50
BD	2.00	42.20	SG	1.85	44.50	SG	5.20	40.60	BD	1.20	40.60
BD	1.90	42.60	SG	0.92	40.80	SG	3.30	39.60	BD	4.10	46.10
BD	1.90	41.60	SG	0.91	45.60	SG	3.50	40.60	BD	2.20	43.50
BD	2.00	44.70	SG	0.60	45.60	SG	3.30	39.80	BD	1.00	41.00

Appendix 6: Chemical characteristics of soils

CROP	LOCATION	Farms	pH top soil	pH sub soil	Total N top soil (%)	Total N subsoil (%)	Available P top soil (ppm)	Available P subsoil (ppm)	Available K top soil (%)	Available K subsoil (%)	Total C top soil (%)	Total C sub soil (%)
Maize	SG	SGJD	6.28	6.15	0.10	0.14	25	40	0.72	0.56	0.88	1.57
Maize	SG	SGJM	5.87	5.64	0.15	0.14	10	20	0.52	0.26	1.66	1.26
Maize	SG	SGLK	6.49	6.42	0.14	0.14	25	35	1.50	1.22	1.53	1.20
Maize	SA	SAKT	6.01	5.96	0.13	0.12	70	35	1.15	0.70	1.39	1.21
Maize	SA	SABD	6.06	6.01	0.13	0.12	10	25	1.12	0.66	1.51	1.27
Maize	SA	SAHH	6.11	5.78	0.14	0.12	80	30	0.78	0.60	1.28	1.06
Maize	BD	BDND	7.33	6.62	0.14	0.13	40	25	0.78	1.22	1.60	1.42
Maize	BD	BDDW	6.54	6.55	0.14	0.13	20	25	1.24	1.20	1.60	1.13
Maize	BD	BDGF	6.37	5.89	0.04	0.09	35	20	0.98	0.36	0.20	0.61
Maize	DK	DKJG	5.99	5.89	0.12	0.11	70	40	1.26	0.56	0.96	0.82
Maize	DK	DKMK	5.96	6.10	0.12	0.09	35	20	0.86	0.32	0.98	0.71
Maize	DK	DKED	6.18	6.14	0.11	0.09	30	15	1.20	0.84	0.85	0.62
Beans	SG	SGJD	6.07	6.16	0.13	0.12	10	30	0.60	0.70	1.14	1.00
Beans	SG	SGJM	5.84	6.11	0.14	0.11	10	25	0.44	0.26	1.49	0.88
Beans	SG	SGLK	6.35	6.13	0.13	0.12	35	15	1.48	0.70	1.49	1.00
Beans	SA	SAKT	6.00	5.93	0.12	0.11	90	45	1.00	0.64	1.35	0.97
Beans	SA	SABD	6.02	6.12	0.13	0.14	10	20	0.98	0.66	1.45	1.30
Beans	SA	SAHH	6.08	6.10	0.14	0.14	55	90	0.90	0.58	1.23	1.22
Beans	BD	BDND	6.40	6.26	0.12	0.12	15	25	0.88	0.30	1.40	1.25
Beans	BD	BDDW	6.62	6.75	0.15	0.14	50	15	1.50	1.14	1.60	1.35
Beans	BD	BDGF	6.48	5.84	0.11	0.11	40	15	1.18	0.36	0.98	0.87
Beans	DK	DKJG	5.94	5.91	0.13	0.11	65	15	1.12	0.56	1.18	0.73
Beans	DK	DKMK	6.05	6.02	0.11	0.12	25	25	0.98	0.68	0.89	1.06
Beans	DK	DKED	6.35	6.38	0.14	0.07	100	75	1.14	0.78	1.23	0.42

Appendix 7: Physical characteristics of soils

Locations	Farms	Soil Depth (cm)	Crop Fields	Sand (%)	Clay (%)	Silt (%)
SG	SGJD	Top	Maize	10	70	20
SG	SGJD	Sub	Maize	8	72	20
SG	SGJD	Top	Beans	6	74	20
SG	SGJD	Sub	Beans	2	78	20
SG	SGJM	Top	Maize	10	70	20
SG	SGJM	Sub	Maize	2	78	20
SG	SGJM	Top	Beans	8	72	20
SG	SGJM	Sub	Beans	4	74	22
SG	SGLK	Top	Maize	6	68	26
SG	SGLK	Sub	Maize	10	74	16
SG	SGLK	Top	Beans	10	62	28
SG	SGLK	Sub	Beans	8	76	16
SA	SAKT	Top	Maize	18	62	20
SA	SAKT	Sub	Maize	12	72	16
SA	SAKT	Top	Beans	34	46	20
SA	SAKT	Sub	Beans	12	70	18
SA	SABG	Top	Maize	10	68	22
SA	SABG	Sub	Maize	8	74	18
SA	SABG	Top	Beans	12	72	16
SA	SABG	Sub	Beans	8	78	14
SA	SAHA	Top	Maize	16	62	22
SA	SAHA	Sub	Maize	8	68	24
SA	SAHA	Top	Beans	12	62	26
SA	SAHA	Sub	Beans	8	68	24
BD	BDND	Top	Maize	22	48	30
BD	BDND	Sub	Maize	20	60	20
BD	BDND	Top	Beans	12	66	22
BD	BDND	Sub	Beans	20	64	16
BD	BDDT	Top	Maize	12	68	20
BD	BDDT	Sub	Maize	10	76	14
BD	BDDT	Top	Beans	14	64	22
BD	BDDT	Sub	Beans	10	76	14
BD	BDGD	Top	Maize	10	70	20
BD	BDGD	Sub	Maize	8	78	14
BD	BDGD	Top	Beans	10	72	18

Appendix 7: Physical characteristics of soils ………………..Continued

Locations	Farms	Soil Depth (cm)	Crop Fields	Sand (%)	Clay (%)	Silt (%)
BD	BDGD	Sub	Beans	8	78	14
DK	DKJG	Top	Maize	10	68	22
DK	DKJG	Sub	Maize	14	72	14
DK	DKJG	Top	Beans	8	64	28
DK	DKJG	Sub	Beans	8	68	24
DK	DKMK	Top	Maize	10	70	20
DK	DKMK	Sub	Maize	6	78	16
DK	DKMK	Top	Beans	10	72	18
DK	DKMK	Sub	Beans	4	74	22
DK	DKED	Top	Maize	14	64	22
DK	DKED	Sub	Maize	6	70	24
DK	DKED	Top	Beans	12	68	20
DK	DKED	Sub	Beans	10	78	12

Appendix 8: Characteristics of manure

Location	Farms	Total organic carbon (%)	Total nitrogen (%)	Total phosphorous (%)	Total potassium (%)
SG	SG1	11.40	2.45	0.34	0.39
SG	SG2	7.40	3.50	0.55	1.49
SG	SG3	8.38	2.10	0.44	0.29
SG	SG4	5.94	2.10	0.59	2.12
SG	SG5	6.63	1.75	0.34	1.24
SG	SG6	4.69	1.75	0.26	1.30
SA	SA1	9.99	1.75	0.22	0.51
SA	SA2	8.34	3.50	0.50	0.42
SA	SA3	8.20	2.45	0.47	0.95
SA	SA4	5.21	2.45	0.33	1.93
SA	SA5	5.83	1.75	0.11	2.81
SA	SA6	5.64	1.75	0.42	1.17
BD	BD1	7.51	2.10	0.27	2.02
BD	BD2	6.51	2.45	0.33	1.30
BD	BD3	4.18	1.75	0.33	0.86
BD	BD4	11.2	2.45	0.34	0.48
BD	BD5	7.11	2.45	0.39	0.58
BD	BD6	5.96	1.75	0.50	0.58

Appendix 9: Forage biomass production in the study area

Seasons	Locations	Sites	Dominant Plant forms	DM forage biomass (t/ha)
2017	BD	BD1	Grass	7.10
2017	BD	BD1	Grass	4.47
2017	BD	BD1	Grass	4.29
2017	BD	BD1	Grass	4.30
2017	BD	BD1	Grass	5.07
2017	BD	BD1	Grass	4.06
2017	BD	BD1	Grass	4.06
2017	BD	BD2	Grass	6.36
2017	BD	BD2	Grass	10.72
2017	BD	BD2	Grass	6.61
2017	BD	BD2	Grass	3.20
2017	BD	BD2	Grass	2.13
2017	BD	BD2	Grass	6.93
2017	BD	BD2	Grass	7.46
2017	BD	BD3	Grass	4.31
2017	BD	BD3	Grass	7.42
2017	BD	BD3	Grass	7.09
2017	BD	BD3	Grass	6.71
2017	BD	BD3	Grass	7.22
2017	BD	BD3	Grass	6.50
2017	BD	BD3	Grass	6.19
2017	SG	SG1	Grass	3.20
2017	SG	SG1	Grass	4.26
2017	SG	SG1	Grass	5.86
2017	SG	SG1	Grass	5.22
2017	SG	SG1	Grass	8.52
2017	SG	SG1	Grass	5.33
2017	SG	SG1	Grass	4.26
2017	SG	SG2	Grass	1.92
2017	SG	SG2	Grass	3.08
2017	SG	SG2	Grass	3.17
2017	SG	SG2	Grass	3.16
2017	SG	SG2	Grass	4.18
2017	SG	SG2	Grass	4.18
2017	SG	SG2	Grass	5.23
2017	SG	SG3	Grass	5.07
2017	SG	SG3	Grass	4.48

……………Appendix 9 continued…….

Forage biomass production in the study area

Seasons	Locations	Sites	Dominant Plant forms	DM forage biomass (t/ha)
2017	SG	SG3	Grass	3.54
2017	SG	SG3	Grass	5.03
2017	SG	SG3	Grass	4.03
2017	SG	SG3	Grass	5.03
2017	SG	SG3	Grass	6.04
2017	SA	SA1	Grass	5.21
2017	SA	SA1	Grass	7.85
2017	SA	SA1	Grass	3.79
2017	SA	SA1	Grass	3.47
2017	SA	SA1	Grass	4.34
2017	SA	SA1	Grass	3.91
2017	SA	SA1	Grass	5.64
2017	SA	SA2	Grass	8.84
2017	SA	SA2	Grass	8.35
2017	SA	SA2	Grass	6.93
2017	SA	SA2	Grass	8.91
2017	SA	SA2	Grass	7.23
2017	SA	SA2	Grass	4.91
2017	SA	SA2	Grass	9.83
2017	SA	SA3	Grass	4.93
2017	SA	SA3	Grass	4.99
2017	SA	SA3	Grass	2.97
2017	SA	SA3	Grass	4.40
2017	SA	SA3	Grass	3.43
2017	SA	SA3	Grass	4.40
2017	SA	SA3	Grass	2.94
2016	KQ	KQ1	Grass and shrubs	6.91
2016	KQ	KQ1	Grass and shrubs	15.21
2016	KQ	KQ1	Grass and shrubs	8.00
2016	KQ	KQ1	Grass and shrubs	8.37
2016	KQ	KQ1	Grass and shrubs	6.28
2016	KQ	KQ1	Grass and shrubs	6.28
2016	KQ	KQ1	Grass and shrubs	6.07
2016	KQ	KQ2	Grass and shrubs	18.99
2016	KQ	KQ2	Grass and shrubs	7.57
2016	KQ	KQ2	Grass and shrubs	11.58
2016	KQ	KQ2	Grass and shrubs	9.40
2016	KQ	KQ2	Grass and shrubs	12.54
2016	KQ	KQ2	Grass and shrubs	10.45

……………Appendix 9 continued…….

Forage biomass production in the study area

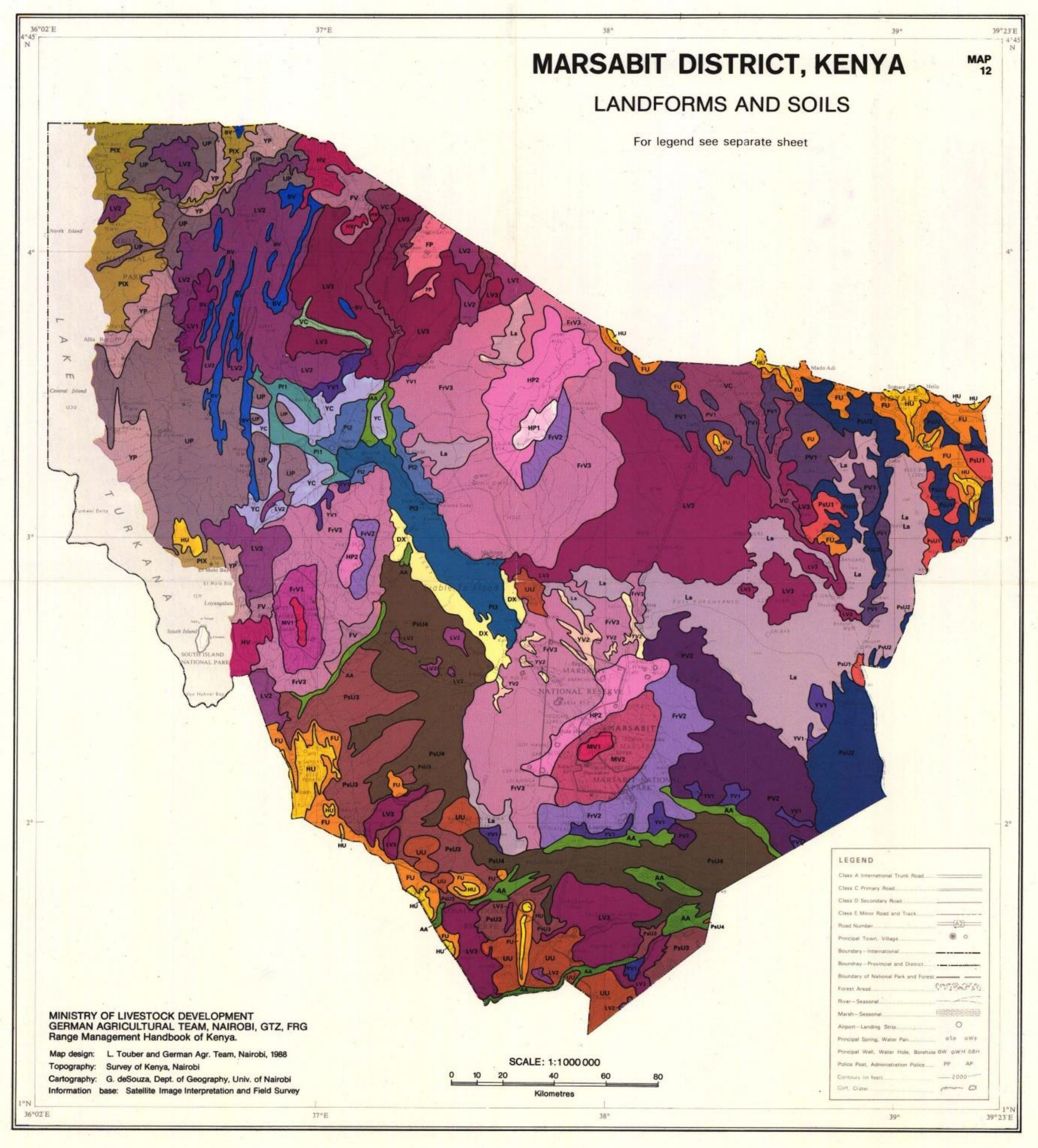
Seasons	Locations	Sites	Dominant Plant forms	DM forage biomass (t/ha)
2016	KQ	KQ2	Grass and shrubs	14.63
2016	KQ	KQ3	Grass and shrubs	6.61
2016	KQ	KQ3	Grass and shrubs	7.73
2016	KQ	KQ3	Grass and shrubs	8.71
2016	KQ	KQ3	Grass and shrubs	8.36
2016	KQ	KQ3	Grass and shrubs	7.63
2016	KQ	KQ3	Grass and shrubs	5.23
2016	KQ	KQ3	Grass and shrubs	6.79
2016	KB	KB1	Grass and shrubs	14.23
2016	KB	KB1	Grass and shrubs	7.46
2016	KB	KB1	Grass and shrubs	15.93
2016	KB	KB1	Grass and shrubs	9.43
2016	KB	KB1	Grass and shrubs	11.00
2016	KB	KB1	Grass and shrubs	9.43
2016	KB	KB1	Grass and shrubs	7.33
2016	KB	KB2	Grass and shrubs	6.31
2016	KB	KB2	Grass and shrubs	10.63
2016	KB	KB2	Grass and shrubs	7.25
2016	KB	KB2	Grass and shrubs	7.93
2016	KB	KB2	Grass and shrubs	4.26
2016	KB	KB2	Grass and shrubs	11.89
2016	KB	KB2	Grass and shrubs	3.96
2016	KB	KB3	Grass and shrubs	8.73
2016	KB	KB3	Grass and shrubs	6.31
2016	KB	KB3	Grass and shrubs	8.31
2016	KB	KB3	Grass and shrubs	3.22
2016	KB	KB3	Grass and shrubs	2.87
2016	KB	KB3	Grass and shrubs	4.10
2016	KB	KB3	Grass and shrubs	3.08
2016	SK	SK1	Grass	6.71
2016	SK	SK1	Grass	6.23
2016	SK	SK1	Grass	6.41
2016	SK	SK1	Grass	6.48
2016	SK	SK1	Grass	5.23
2016	SK	SK1	Grass	5.23
2016	SK	SK1	Grass	6.28
2016	SK	SK2	Grass	5.06
2016	SK	SK2	Grass	6.08
2016	SK	SK2	Grass	5.35
2016	SK	SK2	Grass	6.19
2016	SK	SK2	Grass	5.16

……………Appendix 9 continued…….

Forage biomass production in the study area

Seasons	Locations	Sites	Dominant Plant forms	DM forage biomass (t/ha)
2016	SK	SK2	Grass	5.16
2016	SK	SK2	Grass	4.13
2016	SK	SK3	Grass	5.41
2016	SK	SK3	Grass	3.24
2016	SK	SK3	Grass	6.48
2016	SK	SK3	Grass	8.15
2016	SK	SK3	Grass	7.58
2016	SK	SK3	Grass	11.91
2016	SK	SK3	Grass	4.33

Appendix 10: Soil types in Marsabit



Appendix 11: Legend for soil types in Marsabit

LANDFORMS AND SOILS

To accompany map 12

L E G E N D

MAJOR LANDFORM	PREDOMINANT GEOLOGY AND PARENT MATERIAL	MAP UNIT SYMBOL	SURFACE AREA %	SURFACE AREA KM²	TOPOGRAPHY; PREDOMINANT SLOPE %	EROSION HAZARD AFTER REMOVAL OF VEGETATION BY OVER UTILIZATION (E.H.) 1): WATER EROSION SHEET & GULLY	WIND EROSION AND DEPOSITION	CONSTRAINTS TO THE ACCESSIBILITY FOR LIVESTOCK 2): GOAT SHEEP	CAMEL	CATTLE	ADDITIONAL WET SEASON CONSTRAINTS	HAZARDS OF FLOODING, PONDING IN WET SEASON	SOIL PROPERTIES: DRAINAGE CLASS	SOIL DEPTH	COLOUR	SALINITY, SODICITY	ROCKYNESS, STONINESS	TEXTURE	INFILTRATION CAPACITY OF SURFACE SOIL	TOPSOIL ORGANIC MATTER CONTENT
Mountains	Undifferentiated Volcanic Rocks	MV1	0.2	142	Hilly-rolling 8-30%	Moderate - low	Moderate - low	None	Moderate	Moderate	None	None	Well drained	Very deep to shallow	Dusky red to dark reddish brown	Nil	Locally rocky and stony	Clay - clay loam	High	High, > 2% O.M.
		MV2	1.2	800	Highlands - rolling to undulating 3 - 16%	Low	Moderate - low	None	None	None	None	None	Well drained	Very deep	Dusky red to dark reddish brown	Nil	Locally bouldery and stony	Clay - clay loam	High	High
Hills	Basement System Rocks	HU	1.2	813	Irregular steep slopes. Variable	High sheet and gully E.H.	None	Moderate severe	Severe	Severe	None	None	Well drained	Shallow	Dark brown - dark reddish brown	Nil	Rock outcrops; stony and bouldery	Sandy clay loam - sandy loam	Variable	Moderate
	Pyroclastic Rocks	HP1	0.5	141	Highlands with many isolated small hills	Low	Moderate - low	None	None	Slight	None	None	Well - somewhat excessively drained	Moderately deep	Dark brown	Nil	Locally stony	Fine gravelly sandy clay loam	High	High, > 2% O.M.
		HP2	2.6	1758	Gently undulating highlands with small isolated hills	Low sheet E.H. moderate gully	Moderate	None	Slight	Moderate	None	None	Well - somewhat excessively drained	Moderately deep	Brown	Nil	Locally stony and gravelly	Fine gravelly sandy clay loam	High - moderate	High - moderate
	Undifferentiated Volcanic Rocks	HV	0.8	518	Steep irregular slopes variable	Moderate sheet and gully E.H.	None	Moderate	Severe	Severe	None	None	Well - somewhat excessively drained	Very shallow	Dark reddish brown	Locally saline	Rock outcrops: Bouldery extremely stony	Very stony and gravelly clay loam	Moderate	Low
Foot Ridges	Undifferentiated Volcanic Rocks	FrV1	0.8	514	Gentle slopes - 8% and deep gorges	Moderate - high gully E.H.	Low - Moderate	Moderate	Severe	Severe	None	None	Well drained	Shallow - moderately deep	Dark reddish brown	Nil	Stony to very bouldery	Clay loam - clay	Moderate	Moderate - low
		FrV2	2.4	1612	Gentle slopes - 9% deep stream courses	Slight sheet E.H. high gully E.H.	Low - moderate	None	Slight	Moderate	Moderate	None	Moderately well - imperfectly drained	Deep	Dark brown	Locally saline sodic	Locally stony and bouldery	Cracking clay	Low	Low
		FrV3	13.3	8855	Gentle irregular slopes, complex mesorelief	Low sheet and gully E.H.	Moderate - high	Slight	Slight - moderate	Moderate - severe	Locally moderate	None	Well - imperfectly drained	Shallow - deep	Dark reddish brown	Locally saline and sodic	Very stony; bouldery and rocky	Clay loam - clay	Moderate - low	Low - very low
Foot Slopes	Colluvium derived from Basement System Rocks	FU	2.7	1821	Gentle regular slopes, concave - 8%	High sheet and gully E.H.	Low - moderate	None	None	None	None	None	Well drained	Very deep	Dark reddish brown	Nil	None	Sandy clay loam - sandy loam	Moderate - low	Moderate - low
	Colluvium derived from Pyroclastic Rocks	FP	0.4	293	Gentle regular slopes, concave - 5%	Low - moderate sheet and gully E.H.	Moderate - high	None	None	Locally slight	None	None	Well - somewhat excessively drained	Moderately deep - shallow	Brown	Nil	None, locally stony, gravelly	Fine gravelly clay loam	Moderate	Moderate - low
	Colluvium derived from Volcanic Rocks	FV	0.9	586	Gentle concave slope - 5%	Moderate sheet high gully E.H.	Low - moderate	None	Slight	Moderate	None	None	Well drained	Very deep	Dark brown	Locally saline	Stony, surface gravel and stones	Gravelly sandy clay loam	Moderate - low	Low
Lava Plateaus	Undifferentiated Volcanic Rocks	LV1	0.5	310	Almost flat, < 2%	Low	Moderate	None	None	Slight	None	None	Well - imperfectly drained	Very deep	Dark reddish brown	Nil	Locally bouldery at surface	Clay	Moderate	Moderate
		LV2	6.5	4360	Step faulted and undulating - rolling	Moderate tunnel E.H.	Moderate	Slight	Moderate	Severe	None	None	Well drained	Shallow and moderately deep	Dark reddish brown	Nil	Rocky, stony and bouldery	Clay loam	Moderate	Low
		LV3	11.2	7531	Very gently undulating < 2%	Low tunnel E.H.	Moderate - high	None	Slight	Locally moderate	Slight - moderate	None	Moderately well drained	Very deep	Dark reddish brown	Locally saline and sodic	Surface stoniness	Cracking clay	Moderate	Very low
Uplands	Undifferentiated Basement System Rocks	UU	1.9	1282	Undulating - gently undulating 2 - 8%	High sheet E.H.	Moderate	None	None	Slight	None	None	Well drained	Shallow - moderately deep	Dark reddish brown	Nil	Gravelly	Sandy clay loam - sandy loam	Low - very low	Very low
	Pyroclastic Rocks	UP	6.5	4375	Undulating - rolling, convex slopes of 2 - 10%	Low: protective desert pavement	Low	None	Slight - moderate	Moderate - severe	None	None	Well - somewhat excessively drained	Moderately deep to shallow	Brown	Locally saline	Exceedingly gravelly at surface	Very gravelly clay loam	Low	Very low
Piedmont Plains	Alluvium derived from Pyroclastic Rocks	YP	2.3	1515	Gently sloping and deeply dissected	Moderate sheet and gully E.H.	High	None - slight	None - moderate	Slight - severe	Severe at lowest level	Occasional at lowest level	Various: imperfectly - well drained	Deep/variable	Dark reddish brown - grayish brown	Locally saline	Stony surface - very gravelly	Very gravelly clay - clay loam	Moderate - low	Very low
	Alluvium derived from Volcanic Rocks	YV1	1.1	724	Almost flat, < 3%	Moderate gully E.H.	Moderate - high	None	None	None	Occasionally severe	Occasional	Moderately well - imperfectly drained	Very deep	Reddish brown - grayish brown	Locally strongly saline - sodic	Locally stony and gravelly	Clay loam - cracking clay	Moderate - low	Low
	Alluvium derived from Volcanic Rocks with Windblown Deposits	YV2	0.4	270	Almost flat, < 2%	Low	Moderate	None	None	None	None	None - occasional	Well - somewhat excessively drained	Moderately deep	Yellowish brown	Nil - slightly saline	Fine gravelly	Loam - loamy sand	High	Very low
	Alluvium derived from Volcanic Rocks with Lake-Bed Deposits	YC	1.4	956	Very gently undulating < 2%	1. None 2. None - low sheet	1. None 2. High	None	None	None	1. None 2. Slight	1. None 2. Occasional	1. Well drained 2. Excessively drained	1. Deep 2. Moderately deep	Pale brown - yellowish brown	1. Nil 2. Saline	1. Exceedingly gravelly surface 2. Fine gravelly	1. Gravelly clay loam 2. Stratified sandy loam	1. Moderate 2. High	1. Very low 2. Very low
Volcanic Plains	Undifferentiated Volcanic Rocks	PV1	2.8	1865	Almost flat, < 3%	Moderate - high gully E.H.	Moderate	None	None	None - slight	Moderate	Occasional	Imperfectly drained	Very deep	Dark brown	Saline - sodic (?)	Locally surface stoniness	Cracking clay	Moderate	Moderate
		PV2	3.6	2395	Almost flat, irregular mesorelief	Low	Moderate	Slight	Moderate	Severe	Locally moderate	None	Imperfectly drained	Very deep and rock outcrops	Dark brown - dark grayish brown	Saline - sodic (?)	Very frequent rock outcrops	Clay loam - clay	Moderate	Low
Sedimentary Plains	Undifferentiated Sediments mainly from Basement System Rocks	PsU1	0.8	528	Very gently undulating	Moderate sheet E.H.	None	None	None	None	None	None	Well drained	Very deep	Dark red - dark reddish brown	Nil	None	Sandy clay loam - sandy loam	Moderate - high	Low
		PsU2	3.7	2500	Almost flat, < 2%	1. Locally gully 2. Strong sheet	1. High 2. Moderate	None	None	None	Locally severe	Occasional locally	1. Moderately well drained 2. Imperfectly drained	1. Very deep 2. Shallow	1. Dark brown 2. Grayish brown	1. Nil 2. Sodic	None	1. Variable 2. Clay, sandy clay	1. Moderate 2. Very low	1. Low - moderate 2. Very low
		PsU3	3.9	2590	Almost flat, gently undulating mesorelief	1. Moderate - low 2. Strong sheet	1. High 2. Moderate	None	None	None	1. None 2. Slight	1. None 2. Occasional	1. Somewhat excessively drained 2. Moderately well drained	1. Very deep 2. Very deep	1. Reddish brown 2. Brown	1. Nil 2. Locally saline	None	1. Loamy sand 2. Sandy clay loam	1. High 2. Low	1. Low 2. Low
		PsU4	6.7	4500	Almost flat; gently undulating mesorelief	1. Moderate - low 2. Strong sheet	1. High 2. High	None	None	None	1. None 2. Severe	1. None 2. Frequent	1. Somewhat excessively drained 2. Imperfectly drained	1. Very deep 2. Shallow	1. Reddish brown 2. Brown	1. Nil 2. Sodic, saline	None	1. Sand - sandy loam 2. Sandy clay loam	1. High 2. Very low	1. Very low 2. Low
Lacustrine Plains	Lake-Bed Deposits (Chalbi)	PI1	0.6	400	Almost flat, < 2%	Low - moderate sheet E.H.	High	None	None	None	Locally moderate	Locally	Well drained	Very deep	Pale brown	Saline	Gravelly layers	Fine gravelly sandy loam	Moderate	Very low
		PI2	0.7	495	Almost flat - very gently undulating < 2%	Locally sheet E.H.	Locally high	None	None	None	Locally severe	Locally	Moderately well drained	Shallow - moderately deep	Pale brown	Saline	Calcrete outcrops	Sandy loam	Moderate	Low
		PI3	1.8	1225	Flat < 1%	None	High	None	None	None	Severe	Frequent ponding	Poorly drained	Very deep	Brown-olive grey	Extremely saline - sodic	None	Various: Clay	Low - Moderate	Very low
	Lake-Bed Deposits (Turkana)	PIX	2.5	1695	1. Very gentle slopes 2. Badland topography	1. Low 2. High	1. Low - moderate 2. Low	1. None 2. Severe	1. None 2. Severe	1. None 2. Severe	Severe at lowest level	Occasional at lowest level	1. Somewhat excessively drained 2. Excessively drained	1. Very deep 2. Shallow	Pale brown	Locally saline	1. None 2. Locally rocky	1. Sandy - sandy loam 2. Various	1. High 2. Low	1. Very low 2. Very low
Alluvial Plains	Alluvium, Recent	AA	1.7	1165	Almost flat, < 1%	Low sheet and gully E.H.	Moderate	None	None	None	Severe	Frequent flooding	Imperfectly drained	Very deep	Dark reddish brown - pale brown	Locally saline sodic	None	Stratified various	Moderate	Moderate
Bottom Lands	Alluvium and Colluvium from Volcanic Rocks	BV	0.8	595	Very gently sloping < 2%	Low sheet and gully E.H.	Low - moderate	None	None	None	Locally Severe	Locally ponding	Moderately well drained	Very deep	Yellowish brown	Locally saline	Locally shallow calcrete gravel	Fine gravelly sandy clay loam	Moderate	Low
Valley Complex	Volcanic Rocks	VC	2.1	1388	Almost flat and gullied topography	High gully E.H.	Moderate	None	Slight - moderate	Slight - moderate	Locally severe	Occasional locally	Imperfectly drained	Various depth	Various	Locally saline - sodic	Locally rocky; surface stones	Various, mainly clay	Various	Moderate - very low
Dunes	Windblown Deposits of undifferentiated origin	DX	0.9	615	Undulating - rolling mesorelief	1. Low 2. Low	1. High 2. Moderate	None	None	Moderate	1. None 2. Moderate	1. None 2. Occasional	1. Excessively drained 2. Poorly drained	1. Very deep 2. Locally shallow	1. Reddish brown 2. Dark brown	1. Sodic 2. Saline - sodic	1. None 2. Locally calcrete	1. Sand 2. Sandy clay loam	1. High 2. Very low	1. Very low 2. Low
Lavaflows	Basalts	La	8.4	5625	Almost flat; irregular mesorelief	None	None	Severe - moderate	Severe	Severe	Locally moderate	None	Well drained	Locally deep	Dark reddish brown	Locally saline	Extremely rocky and bouldery	Pockets of clay loam	Moderate	Very low

NOTES:

1) Qualitative estimations only

2) Due to slope steepness, stoniness and rockyness only - vegetation (e.g. dense bush) not taken into account nor distance to watering points, etc. Wet Season: soil muddyness, stickyness, flooding, ponding.