GRAZING PATTERNS, ENERGY EXTRACTION AND LIVESTOCK PRODUCTIVITY IN AGROPASTORAL PRODUCTION SYSTEMS IN KIBWEZI, SOUTHEASTERN KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university

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DEDICATION

TO MY PARENTS

To my parents, who worked tirelessly sometimes under difficulty circumstances to secure an education for me. To my mum,'ASANTE SANA'. To my late dad, I dearly miss your presence, wisdom and witnessing of this work that you laid the foundation for and inspired me to carry on.

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ABSTRACT

The primary energy pathways, energy intake, habitat exploitation patterns and feeding interaction of free ranging agropastoral herds (cattle, goats and sheep) in Kibwezi, a semiarid environment were investigated in two cycles of four consecutive grazing periods. The bites count and herd locations per area methods were used. The water balance and soil loss associated with key perennial grasses subjected to different levels of utilization were assessed using simulated rainfall. Using energy intake-digestibility constraint curves and a growth-consumption rate model, the optimal grass biomass at which energy intake and digestibility equilibrate were derived and the stability properties of the agropastoral system described, respectively. Also, the nature and extent of use of secondary land rights to access grazing resources and the factors affecting their application were analyzed by use of questionnaire and econometric techniques. These analyses aimed at contributing to enhanced livestock productivity in the agropastoral system.

The animals exploited a wide array of plant species. Forage energy for cattle and sheep came primarily from herbaceous plants, while goats largely exploited woody plants. *Enteropogon macrostachyus* was the single largest energy pathway and accounted for over 30% of the total energy intake of cattle. The other important grass resources were *Panicum maximum* (9.9%) followed by *Eragrostis superba* (7.3%). *Combretum exalatum* and *Duosperma kilimandscharica* were the primary energy pathways that accounted for over 10% of total energy intake of goats with seasonal peaks of 18.5 and 17.2%, respectively. Sheep were largely mixed feeders, but *Enteropogon macrostachyus* (16.6%) and *Blepharis integrifolia* (10.3%) were the primary energy pathways. Energy constraint curves revealed that energy intake by cattle was optimized at 460, 420, 470 and 480 gm^{-2} of sward biomass, corresponding to 60.6, 64.3, 62 and 55.5 organic matter digestibility percentage for *Enteropogon macrostachyus*, *Panicum maximum*, *Eragrostis superba* and *Chloris roxyburghiana*, respectively.

The animals had significantly different energy intake within and between seasons. All the animal species had a lower and higher energy intake in the dry and wet seasons, respectively. Energy intake more than doubled and tripled from the late dry to the late wet season, for sheep and goats, and cattle, respectively. All animal species recorded a negative energy balance only in the second late dry season. During this period, 100%, 100% and 67% of the cattle, sheep and goats in the ranch lost weight, respectively. While 50%, 67% and 33% of the cattle, sheep and goats in the agropastoral areas lost weight, respectively. Based on energy balance, goats maintained a superior position and thus were relatively hardier, followed by sheep and cattle. This was further evident given that 78%, 44% and 33% of the goats, sheep and cattle kidded, lambed and calved, respectively.

During the dry season, areas of concentrated drainage, river valleys, bottomlands and ephemeral drainage ways absorbed a greater feeding load, taking 57.1 to 60% of the grazing time by the animals. In contrast, areas of limited moisture concentration, the open sandy/clay plains, were mainly exploited in the wet season, and accounted for 52.6 to 55.6% of the grazing time. The trophic interaction patterns indicated that goats and cattle had a seasonal mean diet overlap index of less than 0.5 for all forage classes. Sheep and cattle, and sheep and goats had a seasonal mean diet overlap index of greater than 0.5 on grass and forbs, and browse and forbs, respectively. This suggested that during periods of resource scarcity, sheep and cattle or sheep and goats could become competitive feeders for same resources.

Infiltration capacity for sites dominated by perennial grasses increased with increasing stubble height before levelling off towards the highest stubble height. A 50% removal of current growth was the upper limit above which runoffs and sediment loss from the grass stands increased rapidly. Aggregate stability, organic carbon and ground plant cover percentage were the most significant attributes that influenced infiltration capacity. *Panicum maximum* and *Enteropogon macrostachyus* stood out as the most suitable perennial grasses with favourable soil physical properties and infiltration capacity in the study area. From a growth-consumption rate model, a stocking rate of 7 TLUha^{-1} appears to be the upper limit in this agropastoral system, above which the system is destabilized during the growing period.

Seventy percent of the households used secondary rights to secure pasture for their animals, particularly short term loans (64%) and exchange of bulls for ploughing (38%). Use of secondary land rights was positively and significantly influenced by increasing livestock per adult, smallstock to cow ratio, and small farm size per household. The amount of crop residue available and increasing grazing area per adult had a negative effect. Secondary rights gave households flexibility in dealing with pasture shortages during critical periods. Grazing management strategies that enhance a broadly stabilized energy extraction pattern and complementary trophic interactions, augmented by flexible secondary land rights, could be central to sustainable livestock production in such environments.

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LIST OF TERMS AND DEFINATIONS AS USED IN THIS STUDY

C_4 grasses refer to warm season monocots with a few dicots that use four atom carbon compounds as intermediates in their energy synthesis. These plants also have high photosynthetic capacity at high temperature and light intensity both at high and low CO_2 concentrations

Equilibrium system refers to a system that is responsive to grazing pressure. In this system forage availability is the main factor that limits animal populations and animal numbers controls availability of forage

Grazing system refers to a system based almost exclusively on livestock production on natural pastures/vegetation

Grazingland tenure refers to the terms and conditions on which grazingland and associated resources are held and used

Land tenure refers to the terms and conditions on which land resources are held and used

Non-equilibrium system refers to a system that is not responsive to grazing pressure but is largely regulated by abiotic controls, mainly rainfall. That is, climatic variables, mainly rainfall limits forage availability and thus animal numbers

Secondary rights refer to derived rights on using grazingland. This include leasing grazingland for short or longterm use

Stability refers to stable, self-regulating system

System refers to regularly interacting and interdependent components forming a unified whole

CHAPTER ONE

INTRODUCTION

1.1. BACKGROUND TO THE STUDY PROBLEM

Africa today faces a myriad of crises: the food crisis, the energy crisis, the debt crisis, and the economic management crisis. To this list can be added the increasing adverse climatic conditions that have increased the vulnerability to droughts and famine throughout the continent. The food crisis is particularly critical as it directly affects the sustenance of human life. Worldwide, about 800 million people suffer from inadequate food intake (FAO 2000) with over 25% of them residing in sub-Saharan Africa (FAO 1996), mainly in the low potential arid and semiarid zones.

In sub-Saharan Africa, food production has by and large lagged behind consumption. In 1980, for example, per capita food production in the region was estimated at 15% below per capita consumption at the start of the 1970's, and almost 20% at the start of the 1960's. Furthermore, between 1975 and 1992, per capita food production fell by 12% in the region (Nyariki 1997). This situation is projected to exacerbate into the 21st century. In sub-Saharan Africa the population is estimated to grow at the rate of more than 3% compared to food production growth of 2% or less annually (Sansoucy *et al.* 1995). This will create a deficit in a number of food products. For example, meat consumption in the 1993-2020 period is projected to grow by more than 3.5 % per year, lagging behind production growth of 3.4% or less per year, in the region (IFPRI 1999).

This situation has often precipitated high incidences of hunger and malnutrition in the region. For example, during the drought of 1982-1984, Food and Agriculture Organization (FAO) and World Food Programme (WFP) estimated that 3.3 million tonnes of emergency food aid were required for 24 African countries facing critical shortages. Food shortages continued to be felt into the 1990's as a result of poor agricultural performance (FAO 2000). By 2001, agricultural production had lagged behind average population growth rates (approx. 2.5%)

for the third consecutive year (FAO 2001). This scenario has precipitated a food deficiency and dependency syndrome in many parts of sub-Saharan Africa.

In Kenya, food security, like the rest of sub-Saharan Africa, is not promising. Kenya is an agriculture-based economy. Agriculture accounts for 20-30% of the gross domestic product (GDP), of which 10% accrues from livestock. Realized agricultural production is not adequate to meet the food requirements of the country. The country is frequently faced with acute food shortages. For example, in 1980 the total calorie availability from the national food production fell by 10% compared to the 1976 average. The decline in the available food per capita was attributed to a drop in output of livestock products and grains. Adverse climatic conditions are partly to blame. Unfortunately, drought that is the main climatic feature is recurrent and persistent, leaving the country dependent on imports of the major food commodities during these periods.

The dismal performance of the country's agricultural sector in the past decades underlies the prevailing food scarcity. For example, from a real growth rate of 4.4% in 1996, it decelerated to 1.5% in 1999 and to negative 2.4% in 2000. Growth remained weak in 2002 averaging 0.7% (RoK 2003). This has forced the government to emphasize broad self-sufficiency in food production through its various agricultural policy documents: sessional papers No. 4 of 1981, No. 1 of 1986 and No. 3 of 1993, and the current economic recovery strategy document for 2003-2007 (RoK 2003).

A number of reasons account for the decline in the agricultural sector, including inappropriate farming and husbandry techniques that are unsuitable to variations in agro-ecological zones. Thus, this study aimed at determining the critical energy pathways that need to be sustained and improved to enhance livestock productivity in the agropastoral system of the Kamba people residing in Makueni District in southeastern Kenya. This would allow livestock production to play its rightful role in alleviating the prevailing food scarcity. As noted by Schiere *et al.* (2002), the value of energy and especially protein originating from livestock is higher than that of plant protein sources. When livestock potential is harnessed to produce these products, higher levels of food surplus are likely. This suggests that to achieve food security, particularly where livestock is a key component, constraints to livestock production must be adequately addressed.

Agropastoralism represents a mode of resource extraction and use between pure cultivators and pure pastoralists, in the semiarid environments. In contrast to pure pastoralism where the level of operation is largely extensive, agropastoralism is semi-intensive, characterized by reduced spatial mobility, modified animal feeding habits, spatial patterns, and adjusted pastoral techniques (Bonfiglioli 1993).

Besides the unique realities of agropastoralism as a production system, agropastoralists, like pastoralists all over the world and especially in sub-Saharan Africa, are faced with problems of low livestock productivity and land degradation. The main constraint to livestock productivity is inadequate natural supply of feeds both in quantity and quality. Livestock productivity is further constrained by declining land productivity and inappropriate land tenure. Land degradation is caused by inappropriate land use practices, especially overgrazing and debilitating droughts. These problems are assumed to stem partly from the tragedy of the commons (Hardin 1968) or prevailing aridity (Ellis *et al.* 1993, Hjort *et al.* 1999). Approaches for addressing these problems in the past were centred on western models of rangeland management practices that emphasized determining grazing plans and stocking rates (Perrier 1994). In Kenya, for example, the government policy interventions focused on land privatization and appropriation to create grazing blocks and ranching schemes. However, evidence indicates that projects modelled on the ranch approach have often generated negative rates of return, and have favoured wealthier households (McCarthy and Swallow 1999).

Livestock production problems at the agropastoral level are largely attributed to inadequate understanding of the ecology of semiarid environments, particularly the temporal and spatial variability of rangeland production, energy extraction patterns and the role of mobility in sustaining livestock production in these environments (Ellis and Swift 1988). We may also add lack of establishing and enhancing the critical energy pathways that sustain livestock production at different periods of the production cycle.

Semiarid ecosystems are characterized as resilient where forage productivity is driven by climatic variables rather than stocking density. Also, forage compositions are patchy rather than evenly distributed in space; and that an opportunistic, mobile grazing strategy is better suited to these environments (Sandford 1983, Behnke and Scoones 1993). This strategy is under stress partly due to increasing tendencies for sedentarization and individualization of both land and grazing resources. Furthermore, the occurrence of equilibrium dynamics in semiarid areas precipitates negative vegetation shifts under high livestock densities (Coppock 1993), leading to low livestock performance.

In this context, there is concern that the new production system in terms of resource extraction regimes in the semiarid areas is not attuned to enhanced livestock productivity, long-term environmental stability, and secure livelihoods. This is particularly so when the traditionally developed and tested functional strategies on resource utilization are ignored by rural development planners, or constrained by emergent land use policies.

1.2. PROBLEM STATEMENT

The main concern of this study is low livestock productivity in the agropastoral systems of Kibwezi, precipitated by inadequate natural supply of feeds both in quantity and quality. Livestock productivity is further constrained by declining land productivity and inappropriate land tenure in the area.

Livestock constitute the mainstay of rangeland inhabitants. Their importance is indicated by ratios of livestock units to people. In eastern Africa, over 1.9 and 0.6 tropical livestock units (TLU) per person per square kilometer are realized in the arid and semiarid lands (ASALs), respectively. However, livestock productivity in these pastoral or agropastoral areas is low. Low output is due to low off-take rates and low yield per animal. For example, beef and veal output per head of cattle in North America is 281kg whereas yields in Africa and Asia are about half of this. Milk yields are also one tenth and one quarter in Africa and Asia, respectively compared to yields in North America and Europe (Wilson *et al.* 1995). In Kenya, 50% of the total national livestock herd resides in the ASALs. This herd contributes about 1.6 million TLUs for slaughter (Omiti 2003) and about 25% of the total milk output (Omiti and Irungu 2002, Omiti and Njoroge 2003). These production levels are still low due to low livestock productivity. This has resulted in the country continuing to lag behind in earnings from the livestock sub-sector compared to countries with a smaller national herd. For example, Botswana which has half of Kenya's livestock population, livestock contributes 88% of its agricultural GDP compared to Kenya's 30%. Also, Botswana exports meat valued at US$70 million annually while Kenya has not transacted any meaningful meat export (Omiti 2003). Unless the low productivity facing the livestock sector is urgently addressed, the country would continue to underutilize its livestock resources, receive low earnings and risk playing a marginal role in the global livestock product supply.

A number of production constraints are responsible for the low livestock productivity. The main constraint is inadequate supply of natural feeds both in quantity and quality throughout the year. Wandera *et al.* (1996) observed that the quantity and quality of available feeds are critical constraints among smallholder dairy producers in Kenya. However, available feeds continue to account for the greatest share of the total dairy output (Peeler and Omore 1997). Dairy and beef production in Kenya is largely based on natural fodders whose quantity and quality fluctuates widely in response to variation in rainfall and maturation. Also, feeding accounts for 40 to 80% of total animal production costs in the country.

Increasing land degradation in the grazing environment exacerbates low livestock productivity. Rangelands in Africa (cover 60% of the continent's land area) are subjected to human-induced degradation, with 31% of the area estimated to suffer severe loss of productivity (de Leeuw and Reid 1995). The sources of degradation include inappropriate cultivation of marginal areas, deforestation, and grazing. Grazing contributes about 34.5% of the total soil degradation (Greijn 1994). In Kenya, high rates of soil loss of up to 50 tonnes per hectare per year from degraded grazing land in semiarid areas are common (Nyaoro

1996), and over 50% of natural pastures in the southern rangelands of Makueni, Taita-Taveta and Kajiado are degraded (Mnene 2004). The main impacts of livestock include plant defoliation, loss of soil protective cover and reduced regrowth capacity of plants. These effects are reported to increase exponentially with extraction rates (Belsky 1988, Hiernaux *et al.* 1994). In the study area, increasing human population density and associated increasing animal density, expanding cropping patterns into grazing land, and bush encroachment have exacerbated the grazing pressure on the limited grazing land (Pratt and Gwynne 1977).

Besides the above, the combined effects of adverse climatic conditions, frequent crop failures, low livestock productivity, declining land productivity, and land tenure issues in the area have negatively impacted on the rural population. This study, therefore, aims at contributing to improving the efficiency of animal keeping while protecting the environment in the semiarid areas. This is central to achieving sustainable agricultural development and food security in these food deficit areas.

1.3. JUSTIFICATION

In the recent past, the arid and semiarid ecosystems of Africa have experienced unprecedented human population pressure. This has led to fast exploitation of land-based resources through means that are inconsistent with long-term sustainability. The resultant effect has been human-induced degradation of the landscape. This, coupled with recurrent droughts and consequent production failures, has precipitated environmental and food crises characterized by famine, migration and armed conflict for scarce dryland resources.

Increasing population pressure in semiarid areas has induced land use changes from extensive to fairly intensive systems of production (Tiffen *et al.* 1994). This has sometimes occurred without taking into account the suitability of the agro-ecology to the new production systems. For example, the increasing patterns of crop production in the agropastoral areas of Makueni where risks of crop failure are often high (Sombroek and Braun 1980), present a typical case of unsustainable land use. Yet, livestock production that has been the mainstay of agropastoral systems is increasingly constrained by diminishing land area, low plant biomass production occasioned by high runoff and soil loss (Nyaoro 1996, Kironchi 1998), and inappropriate land tenure. Individualized tenure with exclusive rights of use is common and this limits livestock mobility to access grazing resources scattered between cropland.

Besides the aforesaid, inadequate understanding of the grazing ecology of domestic ruminants and resource utilization and extraction patterns of pastoral and agropastoral communities continues to limit exploitation of rangelands. This has partly contributed to the low success rate of past range livestock development in sub-Saharan Africa and Kenya (Hjort *et al*. 1999). Also, few studies (Coughenour *et al*. 1985, Coppock *et al*. 1986) in Kenya have focused on grazing resource extraction, energy flow and utilization in arid and semiarid areas. Other recent studies (Ekaya 1991, Ndungu 1996) have only focused on diet selection and preferences.

The analysis of grazing resource extraction patterns, animal trophic interactions and energy flows over time is key to adjusting livestock feed demands to precipitous changes and feed supply. Such an analysis is also central to defining the key energy pathways that sustain livestock productivity, and thus household livelihoods in these environments. Furthermore, comparing extraction rates with existing stocking rates is important in providing an index of animal impact per unit area of land. This is useful in assessing future trends in grazing environments, and thus forming the basis for ecological monitoring, an important element of natural resource management and conservation. Also, improved understanding of various human management systems and their potential to adaptation and change is a critical research area for addressing secure livelihoods.

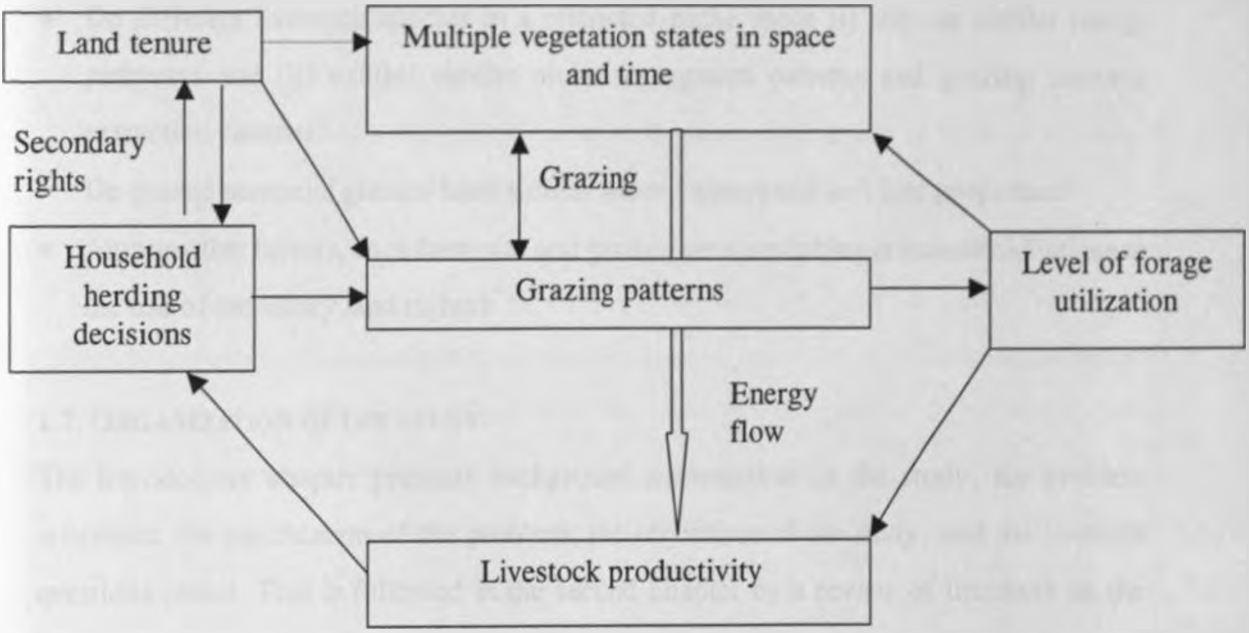
The combined effects of unsuitable land use, land degradation and paucity of information on indigenous production systems *vis à vis* requisite interventions have partly contributed to rural poverty and, in particular, food poverty. In Eastern Province, over 20% of the population is food-poor, with Makueni District having over 70% its population falling below the food poverty line (RoK 2000). Understanding of grazing resource extraction and energy flow patterns in space and time are basic to designing of strategic interventions to enhance livestock productivity, protect the environment and secure people's livelihoods. Therefore, the current study will provide resource extraction and energy flow analysis to determine critical energy pathways that can be improved and sustained to enhance livestock productivity in the agropastoral context of Kibwezi in Makueni District.

1.4. CONCEPTUAL FRAMEWORK

The trade-offs between resource extraction patterns and regimes to realize secure livelihoods, while maintaining environmental integrity continues to dominate the sustainable development agenda. Yet, research connecting the use of resources with changes in production systems and consumption patterns is fairly undeveloped. However, important insights into how societies balance resource extraction, use and conservation can be gained through detailed studies in resource flows at various temporal and spatial scales. Also, resource flow analysis interfaces well with environmental impact assessment and thus presents opportunities for designing strategies for sustainable environmental management.

The current study applies resource flow analysis to determine important grazing resource energy flow pathways that contribute significantly to livestock productivity in an agropastoral production system. Through this analysis, strategic interventions aimed at enhancing energy flow to increase livestock productivity can be formulated. This will partly include the identification and management of key grazing resources, and application of energy subsidies such as crop residues to maintain desired levels of livestock production. Also, the study attempts to map the threshold use of some key forage species to environmental protection, and underpins the role of land tenure in the utilization of grazing resources. The important linkages of this study are illustrated in Figure 1.2.

Figure 1.2. Linkages between grazing resource extraction, energy flow and livestock productivity



1.5. OBJECTIVES

The main objective of this study was to analyze resource extraction patterns, extraction rates, energy flow and their influence on livestock productivity and the environment in agropastoral production system of Kibwezi, Makueni District, southeastern Kenya. The specific objectives were to:

- Analyze grazing resource extraction patterns and energy flow patterns and their impacts on livestock (cattle, sheep and goats) productivity in an agropastoral system.
- Characterize the seasonal resource utilization pattern and habitat exploitation patterns of free ranging agropastoral herds.
- Determine the effects of different levels of utilization of key grazing resources on water balance and soil loss in the grazing environment.
- Document the nature and extent of application of secondary land rights to access grazing resources.
- Describe the stability properties of agropastoral production system.

1.6. RESEARCH QUESTIONS

The following research questions form the basis of this study:

- Do different livestock species in a restricted niche space (i) rely on similar energy pathways and (ii) exhibit similar niche segregation patterns and grazing resource extraction patterns?
- Do grazed perennial grasses have similar water balance and soil loss properties?
- Among other factors, does farm size and grazing area available per household influence the use of secondary land rights?

1.7. ORGANIZATION OF THE STUDY

The introductory chapter presents background information on the study, the problem statement, the justification of the problem, the objectives of the study, and the research questions tested. This is followed in the second chapter by a review of literature on the grazing patterns and diet selection at the landscape, and patch and feeding station levels by grazing animals. In this chapter, other issues of relevance are also addressed including foraging efficiency, energy flow and livestock productivity; animal trophic interactions; grazing in equilibrium and non-equilibrium dryland ecosystems; land tenure and livestock productivity; and models for estimating livestock production as well as environmental stability. The area of study and procedures adopted for data collection and analyses are described in the third chapter. Detailed empirical analyses and discussions are presented in Chapters Four and Five. The last chapter ties up the discussions, summarizes the main findings and conclusions, and suggests some recommendations for grazing systems in similar settings.

CHAPTER TWO

LITERATURE REVIEW

2.1. INTRODUCTION

Pastoralism and agropastoralism are predominant land use strategies in the drylands of the world. These arid and semiarid areas (ASALs) cover about 35% of the earth's land surface and support 500-600 million people, majority of who are pastoralists and agropastoralists. They contribute a large share of the 40% of the total food energy derived from livestock products and other non-cereal products in half of sub-Saharan Africa with the highest risk of food insecurity (FAO 1993). In Kenya, 25-30% of the human population lives in ASALs, which also supports 50% of the cattle, 75% of small stock, and 100% of camels (Brown 1994, RoK 1997). Throughout the developing world, ASALs provide 90-100% of the nutrients consumed by domestic livestock (ILRI 1999).

In these lands, livestock herding is the main livestock control method, with grazing pressure and prescribed fire manipulations providing the most important management tools (Wilson *et al.* 1988). Grazing is a major disturbing force, owing not only to the effects of defoliation (Hodgkinson 1992), but also to the trampling effects on soil properties (Warren *et al.* 1986). Therefore, grazing and grazing management are critical processes to economic utilization of rangelands or their destruction.

To optimize rangeland utilization, given the high level of environmental complexity in rangelands, has been and still continues to be a great challenge. To meet the challenge of optimizing livestock production from these lands will partly require a greater understanding of the temporal and spatial dynamics of the grazing process, and the grazing potential *vis à vis* the strategic value of the various grazing/browsing resources available. The sections that follow address issues on grazing patterns and diet selection from the landscape to the station level of feeding, foraging efficiency, stability of the grazing environment, grazing land tenure, and livestock productivity.

2.2. GRAZING PATTERNS AND DIET SELECTION AT THE LANDSCAPE LEVEL

Grazing patterns depict the movements on and use of the landscape by the grazing animals. These are established once an animal has oriented itself in the landscape, and begins feeding along a grazing path based on spatial and species choice. At the landscape level, those physiognomic and thermal features that influence animal movement patterns characterize diet selection. These include boundaries, distribution of plant communities, degree of accessibility, and distribution of water, thermal and mineral foci.

The distribution of thermal foci that allows animals to maintain body temperatures in a landscape relative to water location interacts with prevailing winds to affect the amount of potential grazing pressure a site will receive (Stuth 2002). Most herbivores are central place foragers, that is, they graze from a central point, usually a water point, from which they seek out the most efficient energy sources of forage. Once the animal sets into grazing from the central place, the subsequent distance covered by the animal is determined in part by digestive capacity, potential harvest rate of forage encountered, potential grazing velocity, and the level of satiety of the animal (Walker *et al.* 1989). Once satiated, the animal either returns to a thermal, water or strategic bedding site depending on the thresholds of these various needs. The interaction of thermal regulation and digestive capacity is responsible for the noticeable piospheres or rings of utilization, which diminish in area with the distance from the central place (Stuth 2002). The ceiling on grazing activity is set by the grazing time per day.

Grazing time is a function of forage quality, thermal balance and short-term stability of forage supply. Grazing time decreases as the digestibility of forage available declines and the retention time of ingested feed increases. When forage supply is restricted, animals compensate by increasing the grazing time. However, if the animals are in a severe energy deficit, they tend to give up the search for food due to the high costs of travel relative to the energy gained from edible forage located (Coleman *et al.* 1989). From the landscape level, the animal settles to graze on a particular plant community or patch.

2.3. THE PATCH LEVEL OF DIET SELECTION

Patches are more homogeneous units of a habitat. They are delimited by the type of plant species present, their spatial arrangement, and structural configuration. Thus, a patch defines a spatial aggregation of bites over which instantaneous intake rate remains relatively constant (Illius and Hodgson 1996). At the patch level, the animal's selection of a given plant community is largely related to those attributes that influence its ability to harvest nutrients. Senft *et al.* (1987) established that forage quantity and quality were closely related to the ratio of the time spent grazing in a given community relative to the area occupied by the community within the landscape. The abundance of seasonally preferred plant species also influences the patterns of plant community use (Senft *et al.* 1985). Thus, communities that afford animals high harvest rates per unit of grazing time are preferred. The greater the density of high quality food species, the lower the grazing velocity, therefore the greater residence time and intake attained relative to other communities available to the animal (Senft *et al.* 1987). However, grazing preference based on occupancy (time spent) to area ratios can be misleading if assumed to reflect the food value of a site. A clear functional nature of landscapes with respect to grazing use is obtained by factoring the utilization to herbage mass ratios (Stuth 2002).

When area to occupancy ratios are contrasted with utilization to herbage biomass ratios for the same site, four major preference categories arise (Stuth 2002):

- Grazing preferred sites that have high occupancy to area ratios and high utilization to herbage biomass ratios.
- Grazing avoided areas that contain low-value plant species or are inaccessible.
- Terrain constrained sites that have high occupancy times yet little utilization relative to herbage biomass in the pasture.
- High impact grazing sites that have high utilization relative to herbage mass in the pasture.

Therefore, patch configurations and their interrelations to occupancy time and forage use offer opportunities to manipulate landscapes for improved animal use.

2.4. THE FEEDING STATION LEVEL OF DIET SELECTION

A feeding station is established once an animal stops walking, lowers its head and takes a bite. At this level, foraging behaviour is characterized by search time, time spent travelling between stations, biting rates (number of bites per unit time) within a feeding station, and duration of biting while at a feeding station (Stuth and Searcy 1987). Animals select fewer plant species that offer the maximum amount of green forage per bite within the primary food group. This may lead to a drop in bite rate. If forage becomes limiting during these high quality periods, animals intensify searching to acquire an adequate daily energy intake until their primary food group is depleted (Stuth 2002). Consequently, as the season progresses and the amount of senescent material in the canopy increases, animals reduce search time between feeding stations and increase selection time at the feeding station level. This suggests that each feeding station is more fully exploited during these times and intraspecific competition becomes most critical. To minimize the adverse effects of declining forage supply, herders often split their herds into smaller feeding groups and disperse over a wider area of the landscape.

2.5. THE RUMINANT GRAZING STRATEGY

The ruminant's digestive system is adapted to a particular diet. Ruminants range in specialization from concentrate selectors through intermediate feeders to bulk feeders. Grazing ruminants are specialized for efficient foregut fermentation with a lower rate of passage. They are specialized for a diet of digestible cellulose and not well suited to consuming large amounts of indigestible fibre, plant materials with concentrated secondary compounds or diets low in fibre (Fisher 2002). In this respect, cattle and sheep are identified as grazers, while goats are intermediate between concentrate and grazing ruminants (Hoffman 1988). Having a rumen does not necessarily maximize intake of energy and nutrients by ruminants. Ruminants are constrained by the relatively low rates of passage from the rumen, and the reduction in feed value as large amounts of soluble carbohydrates, starch and proteins are fermented in the rumen by microbes before absorption in the hindgut (Van Soest 1994). Thus, to maximize energy intake, ruminants have to feed on forages of relatively high nutrient digestibility and energy content (Fisher *et al.* 1999).

2.6. FORAGING EFFICIENCY, ENERGY FLOWS AND LIVESTOCK PRODUCTIVITY

Animals in grazing ecosystems are faced with the problem of meeting energy and nutritional requirements particularly where the quantity and quality of forage vary widely in space and time. This is so in the tropical savannas that include the arid and semiarid areas. In these areas variations in forage quantity and quality are determined by rainfall variability (Sinclair 1975, Frank and McNaughton 1998) and soil fertility gradients (McNaughton 1990). These environmental gradients not only give rise to nutrient rich or nutrient poor grazing areas but also determine nutrient availability and energy flow at all trophic levels in tropical savannas. This situation affects grazing or foraging efficiency.

Grazing efficiency is influenced by foraging decisions. Foraging decisions influence the dietary quality and the energy and nutrient intake efficiency. Thus, grazing efficiency is important in balancing time invested in energy and nutrient intake with non-feeding activities such as rest, reproduction and travel (McNaughton 1984, Spalinger and Hobbs 1992). Grazing animals move along their grazing pathways, seeking out productive and nutrient rich areas. They match grazing time per plant community to the forage resource available (Senft *et al.* 1987), spending less time per feeding station as desirable forage availability declines (Ruyle and Dawyer 1985). Thus, animals adjust their vegetation utilization patterns in relation to the vegetation's productivity (Bailey *et al.* 1996), congregating and producing lawns where productivity is high and dispersing from areas with low productivity (McNaughton 1984).

Forage yield per bite for grazing animals is positively correlated with plant biomass per unit volume, that is, biomass concentration (Ludlow *et al.* 1982, Prins 1992). When forage biomass concentration is below critical levels, grazing animals may be unable to acquire sufficient energy and nutrients for maintenance and production (Chacon *et al.* 1978). Frank and McNaughton (1998) showed that biomass concentration was highest in the wet season in areas where animals were present and that seasonal migrations in grazing ecosystems allow animals to simultaneously maximize dietary energy and nutrient content as well as biomass obtained per bite. Thus, the positive relationship between forage nutrient content and forage biomass concentration is critical as it averts the potential difficulty of simultaneously optimizing forage quality and foraging efficiency. Also, Oba *et al.* (2000) noted that grazing improves energy flow by stimulating more plant production. Grazing reduces accumulation of standing dead materials and stimulates new biomass production. This live and concentrated biomass is efficient in converting rainfall into dry matter production. This biomass is then harvested and converted to energy by the grazing animals. Animal foraging is enhanced through various grazing strategies and strategic animal movements.

Animal movements are not only important in facilitating grazing different sites, but also allow forage to accumulate on ungrazed ranges for use during bottleneck periods such as dry periods. The rate at which animals move through different portions of the grazing area affects the aggregate grazing patterns. Animals move slower through nutrient-rich patches as they spend more time biting and processing the abundant forage (Laca *et al.* 1994a). They spend less time on nutrient-poor patches (Ruyle and Dawyer 1985). Thus, the spatial heterogeneity in food resources allows livestock to selectively occupy the patches yielding highest gains. High forage quality is associated with accelerated total nutrient and energy flow to the herbivores even when total net primary productivity is low (Coughenour 1991).

In pastoral and agropastoral systems where risks of crop failure are high, livestock provides the main avenue for energy extraction and conversion into useful products to support people's livelihoods. Energy extraction and nutrient flow through the herbivore-human food chain depends on primary production and energy extraction rates. Stobbs (1973a) noted that the quantity of herbage harvested in each bite of animals grazing tropical swards, depends on the canopy structure. On leafy swards, feed per bite is a function of the amount of herbage within the area covered by the maximum sweep of the tongue and is therefore largely related to leaf yield and leaf bulk density (Stobbs 1973b). Thus, highest leaf yields and bulk densities result in largest bites (Stobbs 1975).

Energy availability from forages is limited by fibre concentration, which is slowly and incompletely digested (Baumont *et al.* 2000). Grasses have more fibre than legumes, especially in leaves. Ruminants digest 40-50% of legume fibre and 60-70% of grass fibre (Buxton and Redfearn 1997). Fibre concentration increases with maturity of plants. Stems have more fibre than leaves, partly because stems contain more structural and conducting tissues than leaves. Thus, stems decline in digestibility more rapidly with increasing plant maturation than leaves. In addition to fibre concentration increasing within stems and most leaves with maturity, fibre concentration also increases in the total forage because the leaf to stem ratio decreases as plants mature. The portion of digestible energy obtained from fibre (NDF) varies from 20-40% for legumes (60-80 % from cell solubles) and from 50-80% for grasses (20-50% from cell solubles) (Baumont *et al.* 2000). Thus, most of the digestible energy in legumes comes from cell solubles, not from fibre. This explains the tendency of browsing animals to browse more on current growth.

Wilson and Martens (1995) identified five structural limitations to fibre digestion in grasses: 1) Microbial degradation can proceed only from the interior of lignified thick-walled cells because the lignified middle lamella and primary wall are indigestible; 2) Particles pass from the rumen quickly in comparison with digestion rate so that 20% or less of thick-walled cells can be digested; 3) Access to cell interiors is not instantaneous because many cells comprising fibre particles are not exposed by mastication; 4) The low surface area to volume ratio of thick-walled cells limit their digestion; and 5) Presence of phenolic compounds within cells may be toxic to fibre-degrading bacteria in the rumen. Therefore, physical barriers to fibre digestion have a significant influence on fibre degradability.

In a review of forage characteristics that influence nutrient intake in ruminants, Baumont *et al.* (2000) noted that ruminants feed selectively to maximize energy intake and thus their reproductive output. At pasture, energy intake by ruminants is subject to two constraints: time per bite, that is, the time required to harvest a bite and the time required to masticate the harvested material (Newman *et al.* 1994, Prache 1997). Bite size is determined by the ease with which the sward is gathered and sheared. On vegetative swards, sward height and bulk density are the main determinants of bite size and instantaneous intake rate (Burlison *et al.* 1991). Sward height determines bite depth, which increases linearly with sward height but negatively with sward density (Laca *et al.* 1992, Burns and Sollenberger 2002). On mature swards, bite size is affected by the mass of stems and presence of dead material. Stem mass increases down the canopy. High concentration of stems reduces bite size as stems increase the shearing force and thus reduce the amount harvested per bite (Illius *et al.* 1995). Also, lower layers of swards contain more neutral detergent fibre (NDF) than upper layers. Neutral detergent fibre content in a layer in the sward is negatively correlated with intake and, thus animals alter intake rate according to the NDF content of the strata in which they are grazing (Seman *et al.* 1991).

By grazing the top horizon of swards, grazing animals maximize energy and nutrient intake. The top horizon has the greatest proportion of leaves, and a higher concentration of nutrients. Leaves require less chewing than stems, and exhibit faster rates of ingestion, digestion and rate of passage (Mcleod *et al.* 1990). Thus, in the top horizon of swards, animals maximize nutrient intake by increasing the grazing rate rather than the bite weight (Laca *et al.* 1992).

The mass of food in each bite is the variable exerting the greatest influence on intake rate and energy flow to herbivores (Spalinger and Hobbs 1992). Thus, the determinants of bite mass influence foraging decisions and the impacts of grazing on plants. Since the vertical distribution of biomass is skewed, with most of the biomass at the base of the sward, bite mass increases with increasing bite depth. Illius *et al.* (1995) observed that fine-leaved grasses have more tillers than broad-leaved grasses, and require higher forces to graze them. Thus, broad-leaved grass species have higher marginal benefits compared to fine-leaved grass species. Declining marginal benefit with increasing bite force is due to reduced bite rate and reduced energy concentration at lower grazing heights.

Burns and Sollenberger (2002) observed that grazing animals' daily weight gain is positively related to leaf percentage, green herbage mass and leaf mass of warm season pastures. Prache *et al.* (1998) established that green leaf mass per unit area is the best predictor of bite mass and, thus energy intake across different phenological stages of swards. Santos *et al.* (2003) reported that cows spent more time on patches that allowed maximization of intake, obtained through the presence of a greater proportion of preferred plant species. These plant species provide more crude protein and lower neutral detergent fibre. These attributes allow preferred plant species to be grazed more, thus enhancing energy and nutrient intake.

On examining the relationship between sward variables and the nature of patch use experienced by cattle grazing small patches of forage, Ginnett *et al.* (1999) showed that stems affected bite size by restricting bite depth and lengthened time per bite by interfering with bite formation. This reduced intake rate. The presence of reproductive stems of 15cm or more reduced intake more than patches with stems of 5cm or no stems. Sward heights of 3-4cm were limiting for cattle below which they stopped grazing. Also, animals obtain heavier bites on low-density tall swards than on high-density short swards (Laca *et al.* 1992). Therefore, during the dry season when the vegetation is stemmier, grazing animals will have longer time per bite. Burns and Sollenberger (2002) noted that as herbage mass declines, bite weight will also decline. This suggests that grazing animals have to increase bite rate as well as grazing time to meet their energy demands. In the dry season, these requirements are not met as grazing time and bite rate are constrained by heat stress and the stemminess of forage, respectively.

Rates of dry matter intake increase with plant height, leaf size and leaf bulk density in food-concentrated patches (Spalinger and Hobbs 1992, Gross *et al.* 1993). This suggests that cropping rates (grams of plant biomass ingested per unit time) by herbivores increase with sward biomass (Gross *et al.* 1993, Laca *et al.* 1994b). However, on modelling the trade-offs between grass abundance, quality and energy maximization by grazing herbivores, Wilmshurst *et al.* (2000) observed that ruminants maximize daily rates of energy intake by choosing swards of intermediate biomass. As plant abundance increases, plant nutritive quality declines. This increases retention time in the rumen to reduce particle size sufficiently to pass to the hindgut (Illius and Gordon 1992). Thus, high quality-low biomass swards are associated with faster rates of passage, so that more can be consumed to meet the grazing animal's energy requirements, than low quality-high biomass swards.

The trade-offs between food quality and food intake rate are equally central to energy optimization in browsing herbivores. Shipley *et al.* (1999) observed that browsing animals taking large bites could achieve high rates of dry matter intake. However, such bites are of low quality relative to small bites taken from leaves or twigs near the growing point of the plant. Larger bites include more fibrous plant material because structural tissues of plants increase from the distal to the proximal parts of the plant. High fibre concentration, in turn, decreases the digestibility of plant tissue, hence the total amount of energy gained (Robbins *et al.* 1987). Fibre also limits food intake by decreasing the rate of passage of food from the digestive tract (Fryxell *et al.* 1994). Shipley *et al.* (1999) showed that browsing animals tend to select optimal bites to maximize energy intake.

Energy intake for grazers and browsers can be optimized at the point where the cropping and digestive constraint curves intersect (Shipley *et al.* 1999, Wilmshurst *et al.* 1999, Wilmshurst *et al.* 2000). Cropping designates the amount of dry matter ingested per bite. This is dependent on plant biomass. Cropping rates and thus energy intake generally increase with increasing plant biomass but are constrained by the rate at which forage is harvested, chewed and swallowed. Thus, the cropping constraint curve increases asymptotically with increasing plant biomass and tracks the maximum amount of energy an animal can consume in the absence of the digestive constraint. On the other hand, the digestive constraint results from plant maturity. As plants mature, they accumulate structural components and decline in nutritive quality reflected in decreasing digestibility. Thus, the digestive curve tracks the amount of energy an animal can process in the absence of the cropping constraint. Realized energy intake as a function of plant biomass tracks the minimum of the two curves (Shipley *et al.* 1999, Wilmshurst *et al.* 1999, Wilmshurst *et al.* 2000). These constraint curves can be useful tools in determining when to graze/browse tropical swards/browse. However, the complex architectural structure of tropical browse makes it difficult to derive such curves.

Grazing animals are faced with spatial and temporal variation in forage quality and abundance. Wilmshurst *et al.* (1999) showed that energy intake by grazing animals is a positive function of the digestible energy content of forage, but a negative function of sward biomass. That is, daily energy intake is constrained by digestive processes at high sward biomass and cropping processes at lower sward biomass. They further observed that bite rate and bite size were inversely related in dense swards. Thus, animals could maximize energy intake by foraging on swards of low to intermediate biomass where grazing rates and forage digestibility remains reasonably high. This suggests that grazing herbivores should intensely utilize swards of intermediate biomass along their grazing circuit. Gaedke *et al.* (2002) observed that co-limitation on herbivores by food quantity and quality in nutrient-limited ecosystems can be minimized by adaptive adjustments. In this case, herbivores can meet their energy demands by increasing energy use efficiency, enhancing food consumption through compensatory feeding, and selectively feeding on energy-rich food items.

Generally, the intake constraints imposed by the quantity and quality of the vegetation determine the patch and habitats selected by foraging ruminants (Wilmshurst *et al.* 1999, 2000). The quality of the vegetation governs daily energy intake. Crude protein content is the limiting factor over sward characteristics (sward height and bulk density) in daily energy intake, but vegetation characteristics become critical where crude protein is not limiting (Smallegange and Brunsting 2002). Thus, grazing animals selectively occupy patches with the highest daily digestible dry matter intake where foraging costs are relatively low (Wallis DeVries *et al.* 1999).

Grazing animals can also influence energy flow and availability. They enhance plant growth through nutrient enrichment of grazed patches by dung and urine deposition, and by increased light intensity per unit of biomass (Semmartin and Oesterheld 2001). Other positive effects of herbivory on plant growth include increased photosynthetic rate of residual tissues, reduction in the rate of leaf senescence, activation and proliferation of meristems, and increased rain-use efficiency (Ferraro and Oesterheld 2002). Thus, herbivory enhances plant growth, plant production, and facilitates energy flow and availability to higher trophic levels.

In semiarid and arid areas, plant growth or primary production is significantly and positively related to the amount of rainfall (Le Houreou and Hoste 1977, Le Houreou 1984). Primary production responses to rainfall occur as pulses that are rapidly attenuated as the dry season intensifies (Coughenour *et al.* 1990). To cope with this spatial and temporal variability in resources, pastoralists and agropastoralists move their livestock over resource gradients to maximize on opportunities (Coppock *et al.* 1986, Ellis *et al.* 1988).

In this mode of resource extraction, Coughenour *et al.* (1985) reported that about 30% of pastoral food energy originated primarily from dwarf shrub-camel milk, 16% herbaceous plant-cattle milk, with the remaining 54% of the pastoral food following 29 pathways. Thus, pastoralists derived 76% of their food energy from livestock (meat, milk and blood), with 92% of all food energy being derived from pastoral products and the remaining 8% from wild animals and plants (Coughenour *et al.* (1985).

Coppock *et al.* (1986) observed that high concentration of production within patches resulted in higher livestock extraction rates than if plants were uniformly distributed. A high concentration of production in a patch reduces time and energy expended moving from plant to plant. This increases nutrient extraction and energy flow to livestock and thus enhances livestock productivity and household livelihoods. This probably explains the rationale behind the patchy use strategy as practised by pastoralists and agropastoralists.

Pastoral herds harvest a great variety of plants, with diet diversities declining with advancing resource scarcity (Coppock *et al.* 1986). Vavra *et al.* (1977) and Leuthold (1978) reported similar trends. However, for the multispecies pastoral herds, some livestock species show increasing diet diversity. Coppock *et al.* (1986) observed increased diversity of camel diets during the dry spell that is characterized by high resource scarcity. This contributed to a broad, temporally stable niche for the aggregate herd, resulting in an equitable use of the vegetation. However, areas of run-off concentration that supported a high density of woody vegetation with a large percentage of the seed and seedpod producing types were the most selected habitat types. In this case, the drainage ways accounted for 31% of the feeding activity and a use to availability ratio of 6.2.

Coughenour *et al.* (1985) noted that the pastoral food web reflected three complementary modes of resource exploitation. Dependence on the most reliable energy pathway; woody plants to camel milk, opportunistic use of ephemeral herbaceous plants to cattle milk, and contingency conversion of biomass to energy for humans. Thus, diet complementarity and spatial mobility are the most important in habitat resource exploitation. This suggests that land use strategies that result in reductions in the number of livestock species and restrict mobility are inimical to these production systems (Coughenour *et al.* 1985, Coppock *et al.* 1986). This calls for greater understanding of the peoples' resource use strategies as a basis for sound development of their production systems.

2.7. TROPHIC INTERACTIONS

Trophic interactions at the grazing level reflect how grazing animals utilize various food items. Grazing animals undergo ecological segregation to utilize different feed resources, to minimize competition and enhance reproductive fitness (Begon *et al.* 1990). Ecological separation is achieved by animals specializing on feeding discrete but different food items, or by selecting certain food items based on plant characteristics related to quantity or quality (Distel *et al.* 1995, Heitkoning and Owen-smith 1998). An overlap in resource utilization is often with an increase in resource abundance (Gordon and Illius 1989). Competition for resources occurs when there is an overlap and limited resources (Voeten and Prinns 1999). Cattle preferably feed on the grass food group and only switch to other food groups when grass availability is too low as to severely limit daily energy and nutrient intake requirements (Launchbaugh *et al.* 1990). Goats show a high preference for browse regardless of availability and a negative proportional response to grasses. That is, they increase the amount of grass in their diets relative to its availability as the composition of browse and forbs declines. The principal diet for sheep is forbs, but they also consume large amounts of grass (Hanley 1982). Browse is utilized more readily by sheep than cattle but only when grass and forbs are in limited supply (Stuth 2002).

2.8. GRAZING IN EQUILIBRIUM AND NON-EQUILIBRIUM DRYLAND ECOSYSTEMS

The equilibrium and non-equilibrium paradigms have been central to understanding and management of rangelands. The equilibrium paradigm is based on the range succession-retrogression model prompted by clementsian ecology (Westoby *et al.* 1989). In this concept, a given rangeland has a single persistent state (climax or equilibrium community) in the absence of grazing. Succession towards this equilibrium community is a steady process. Grazing pressure produces changes which are progressive and in the opposite direction to the successional tendency. In this model, any undesirable effects such as overgrazing can be offset by resting the range or reducing the stocking rates. This concept does not work well in rangelands were episodic events (such as recurring and severe drought) are more important and grazing effects act intermittently. Such rangeland systems are non-equilibrium systems. In non-equilibrium systems, the range exists in a set of discrete and relatively stable states. Transitions between states are triggered by large changes in climatic factors, grazing pressure, fire or combinations of these ecological factors (Ellis and Swift 1988,Westoby *et al.* 1989).

As noted by Warren *et al.* (1986) and Hodgkinson (1992), grazing pressure is a major disturbing force in dryland ecosystems. A mismatch of grazing pressure in these ecosystems is closely associated with declining land productivity, increasing plant species of low grazing value (Hiernaux 1998) and extensive soil erosion. This situation is often exacerbated because periods of overstocking and severe degradation have been coincidental with major droughts when these ecosystems are highly vulnerable to perturbations. However, perceived overgrazing, particularly in the African drylands, has recently been challenged (Behnke *et al.* 1993). Many areas carry similar or even higher numbers of livestock than they did in the past (Shackleton 1993). Though the vegetation appears degraded, it continues to support these animals. In the case of pastoralism, animals simply track changing food resources associated with recurrent droughts, and optimal stocking levels are higher than those supported under prevailing conditions (Hatch and Stafford-Smith 1997). Theoretically, this challenges the equilibrium scenario that has characterized past range management (Ellis and Swift 1988, Westoby *et al.* 1989, Behnke and Scoones 1993).

Under patch grazing, grazing animals track patches of high nutritive quality. When preferred patches become depleted, livestock switch their feeding to resource patches of lower nutritional value. As a result, mass specific gain in the biomass of herbivores declines gradually with diminishing food resources, and mass specific intake rate by herbivores changes little until hardly any forage remains (Coppock *et al.* 1986). This widening in food quality gradient among resource patches dampens instability and thus both seasonality in vegetation growth and heterogeneity in resource type act to promote stability (Owen-Smith 1999). Therefore, food security and environmental stability are achieved by enhancing resource heterogeneity. Opportunism and tracking resource use strategies become key strategies (Standford 1983) with livestock mobility flattening peaks in grazing pressure and allowing the use of feed resources that are periodically available (Coppock *et al.* 1986, Ellis *et al.* 1988, de Leeuw *et al.* 1999). This patchy use strategy enhances the efficiency of foraging and production in non-equilibrium systems (Coppock 1993, Stafford-Smith and Pick-Up 1993).

Within the drylands, there is episodic occurrence of equilibrium forces in which grazing induced vegetation shifts abound (Coppock 1993). In these areas, prolonged patch grazing can lead to ecosystem degradation. This is because selective grazing and continued grazing pressure lead to death of individual plants. Areas of plant death form impermeable spots that result from soil surface sealing (Bridge *et al.* 1983). Reduced carbon input into the soil further accelerates the degradation of the soil structure (Mott *et al.* 1979). Also, in these areas, higher grazing pressure can lead to the replacement of perennials by annuals, resulting in increased fluctuations in annual forage availability (Bayer and Waters-Bayer 1994). Moreover, as mobility becomes increasingly constrained as in agropastoralism, overgrazing and resource degradation become increasingly evident. This calls for situation analysis of the grazing ecology and resource extraction strategies used, with a view to adjusting or redesigning them to be consistent with sustainable resource utilization and secure livelihoods.

2.8.1. Effects of grazing on vegetation responses

In the drylands of the tropical savannas, C_4 grasses and a woody layer primarily dominate the vegetation. The density and productivity of grasses and woody plants are determined by a number of factors, particularly by the amount of rainfall, availability of nutrients (especially nitrogen and phosphorous), fires and the number and activity of herbivores (Tietema *et al.* 1991). The effects of livestock depend on stocking density, stocking rate and grazing pressure (Coughenour 1991).

Grazing by livestock affects the species composition. productivity and microclimate of the grass layer in the savanna ecosystem. It alters the competitive balance between trees and grasses in favour of trees (Walker *et al.* 1981). Tietema *et al.* (1991) reported heavy grazing in the savanna ecosystem of Botswana, reducing biomass production in the grass layer from 10 to 15 ton ha^{-1} year $^{-1}$. This change was associated with decreasing density of palatable perennials and increasing density of less palatable annuals. Moreover, at high and persistent grazing pressures, the total vegetation cover declined, and unpalatable and often poisonous herbs and shrubs increasingly characterized the grass layer. This was accompanied by physical and microclimatological changes, that is, increasing soil temperatures, erosion, and formation of soil crusts.

The foregoing suggests that annuals increase in number in the early stages of degradation, indicating that under grazing stress, annuals have adaptive advantages over perennials. Ernst and Tolsma (1988) attribute the success of the annuals in colonizing open space to their small size and decumbent growth pattern, apparent heat resistance of their leaves, and a high reproductive capacity with short intervals between flowering and seed production. However, some perennials also have adaptive traits like being unpalatable, spiny and drought resistant. Other adaptive traits by perennials include presence of toxic compounds, low shoot/root ratio and nutrient use efficiency (Tietema *et al.* 1991).

Spatial-temporal utilization patterns reflect how grazing impacts are distributed in space and time. However, the concept of overgrazing being the cause of vegetation change has been challenged (Hoffman and Cowling 1990). Moreover, attributing shifts of vegetation to grazing effects particularly in non-equilibrium systems remains wanting (Ellis and Swift 1988). Evidence suggests that vegetation change has been influenced more by climatic variability than grazing mismanagement (Hoffman and Cowling 1990, Ellis *et al.* 1993). That notwithstanding, when settled agriculture and other forms of land use limit traditional movement or preclude the traditional grazing pattern, overgrazing becomes common (Coughenour 1991). Sinclair and Fryxell (1985) observed widespread patterns of localized overgrazing around developed watering points. Thus, there is need for greater understanding of the impacts of land use on vegetation, particularly at smaller spatial and temporal scales that are more relevant to short term environmental stability and livelihood needs.

2.8.2. Livestock grazing and soil hydrologic response

Livestock grazing has the potential of altering the amount and kind of vegetation, which in turn potentially alters surface hydrological characteristics. Reductions in the amount of vegetation may increase raindrop impact, decrease soil organic matter and aggregate stability, increase surface soil crusting, and decrease infiltration rates (Branson and Owen 1970, Blackburn 1975, Wood and Blackburn 1981). Overgrazed plots consistently produce low infiltration rates compared to livestock exclosures (Mbakaya 1985, Mworia 1996, Kironchi 1992, 1998).

On evaluating the impact of livestock grazing systems on infiltration rates, Mccalla II *et al.* (1984) observed that infiltration rates were consistently higher in the bunchgrass community than in the sodgrass community. The greatest infiltration rates for both communities were maintained with moderate continuous grazing than with heavy continuous grazing. Also, infiltration rates were greatest in both communities during the peak of biological activity. Bunchgrass accounted for 30% of the variation and was one of the strong influences on infiltration rates. Mccalla II *et al.* (1984) concluded that livestock grazing potentially has the greatest impact on grazing sensitive bunchgrass areas whose decline will adversely affect infiltration rates. Rietkerk *et al.* (2000) observed that infiltration capacity increased both with annual and perennial cover. Perennial grass cover had a higher infiltration capacity than annual grass cover. Perennial grass tufts improve water infiltration much more effectively than annual grasses by funnelling rainwater via their basis into their own rhizospheres (Kelly and Walker 1976), stimulating biological activity and decreasing bulk density, thereby increasing retention and availability of soil water. The bulk density beneath perennial grass was significantly lower than on bare ground (Rietkerk *et al.* 2000).

Gamougoun *et al.* (1984) observed no significant differences in infiltration rates between heavily and moderately grazed pastures. This was attributed to organic matter additions from increasers (forbs) that replace grasses when heavily grazed. Total vegetation cover, standing crop, surface roughness, percent bare ground, soil bulk density, soil organic matter and aggregate stability largely influence infiltration rates (Mccalla II *et al.* 1984, MCginty *et al.* 1979). However, on shallow sites with low vegetation production, variation in soil characteristics accounts for a greater proportion of the variation in infiltration, whereas on deep soils, phytomass exerts more influence over infiltration rates (MCginty *et al.* 1979).

Wood and Blackburn (1981) observed that aggregate stability, organic matter content, mulch, standing crop, bulk density and ground cover significantly influenced infiltration rates. Infiltration rates were similar for grazed treatments under heavily and moderately stocked and continuously grazed treatments under high intensity/low frequency grazing. Also, grazing treatments under rested high intensity/low frequency grazing had similar infiltration rates to deferred rotation pastures. Aggregate stability was the primary factor accounting for 86% of the variation in infiltration rates whereby it was the most important variable in 88% of shrub canopy, 100% in bunchgrass interspace and 67% in sodgrass interspace. Also, Wood and Blackburn (1981) asserted that annual grass and forb cover, bulk density (5-8cm) and micro-relief are not significantly correlated with infiltration rates.

On investigating the effect of livestock grazing on soil physical properties and vegetation cover, Chaichi *et al.* (2003) showed that during the grazing season, soil bulk density was higher at 0-15cm compared to 15-30cm of soil profile. Soil porosity decreased in both 0-15 and 15-30cm soil depths. This was attributed to the effects of trampling by livestock. Soil infiltration rate reduced with the grazing period. Rauzi (1966) found a nearly linear relationship between runoff and infiltration. That is, runoff from a heavily grazed watershed (1.35 acre/aum) was 1.4 times greater than from a moderately grazed watershed (2.42 acre/aum) and 9 times greater than from a lightly grazed watershed (3.25 acre/aum). Gifford and Hawkins (1978), on reviewing the impacts of grazing on infiltration, concluded that ungrazed plots have higher infiltration rates than grazed plots, moderate and light grazing intensities have similar infiltration rates, and heavy grazing has definite reductions in infiltration rates over moderate and light grazing.

Although it has been speculated that under some conditions, the hoof action of grazing animals will loosen the soil surface of compacted or crusted soils, actual research shows just the opposite effect (Warren *et al.* 1986a, 1986b, 1986c). The concentration of hoof action under short duration grazing reduces infiltration rate compared to continuous grazing (Thurow *et al.* 1986, Weltz and wood 1986a, Pluhar *et al.* 1987). Other studies (Wood and Blackburn 1981, Gamougoun *et al.* 1984, Pluhar *et al.* 1987) show that grazing systems other than short duration grazing have little effect on infiltration rate but that reductions occur when stocking rates are increased from moderate to heavy. Few studies have evaluated the influence of grazing on soil structure. Wood and Blackburn (1981) found that heavy grazing degraded soil structure by reducing the percentage of water stable aggregates compared to moderate grazing.

Wood *et al.* (1984) reported that grazing treatments have a significant effect on aggregate stability within each plant community (shrub, bunchgrass and sodgrass communities) with water stable aggregates being lowest in high grazing intensity treatments. Sallaway *et al.* (1993) observed increased runoff associated with the replacement of perennials by annuals. This was attributed to reduction in macropore sizes that led to low biological activity by soil fauna. That is, low production on the annual patches result in a low return of plant material to the soil and an exposure of the soil to a harsh microenvironment and thus possibly contributing to reduced soil biological activity.

On testing the effect of annual or perennial grass pastures with or without liming on soil water balance in the high rainfall (>600mm) zone of southern Australia, Heng *et al.* (2001) established that perennial grass pastures with lime extracted 40mm more soil water each year than annual grass pastures. Also, surface runoff, subsurface flow and deep drainage were at least 40mm less from the perennial grass pastures. Thus, perennial grass pasture can play a critical role in enhancing rainwater use efficiency.

Perennial grasses have different water conservation and use efficiency. Marais *et al.* (2003) on applying four levels of moisture stress, that is, 25, 50, 75 and 100% of field capacity, showed that *Cenchrus ciliaris* produced higher yields than *Cynodon hybrid, Digitaria eriantha and Panicum maximum. Panicum maximum* produced the lowest yields. They concluded that *Cenchrus ciliaris* tended to use water more efficiently than *Panicum maximum.* Water use efficiency for all the grasses was higher at 25% water stress. This finding suggests that perennial grasses that use more water to produce will require capturing more water by an improved infiltration rate into their rhizosphere.

The foregoing suggests that grazing alters the natural infiltration-runoff relationships by reducing the protection afforded by vegetation cover, reducing and scattering the litter, and compacting the soil through trampling. The impact of these changes is determined by the intensity of grazing, soil type, climate, topography, livestock management system, and vegetation type (Javadi *et al.* 2003).

2.8.3. Effects of livestock grazing on sediment production

Accelerated soil erosion occurs when man's activities destroy the vegetation cover that minimizes soil loss from the forces of water and wind. The inverse relationship between accelerated erosion and plant cover is well established (Osburn 1956, Thurow *et al.* 1986). Accelerated erosion is the most severe consequence of overgrazing due to the fact that the replenishment of lost soil is a slow process. Therefore, losses of soil result in nearly permanent reductions in grazing capacity. The best protection against erosion lies in establishing and maintaining good vegetation cover.

Gamougoun *et al* (1984) reported that lowest sediment levels were produced in an exclosure and significantly different from those produced under heavily stocked or moderately stocked and continuously grazed pastures. Wood *et al.* (1981) indicated higher sediment production from continuously grazed treatments than from exclosures. They also observed higher sediment production in sodgrass interspaces (94.7 $kgha^{-1}$) than shrubby canopy zones (14.4 $kgha^{-1}$) and bunchgrass interspace (31.9 $kgha^{-1}$). Aggregate stability and organic matter content were the most influential variables in 36% and 32% of predictive equations, respectively. Organic matter influences the soil plasticity by increasing the cohesion of soil particles, especially clay particles. Increased cohesive properties render the soil less vulnerable to erosion. Wood *et al.* (1981) established that perennial grass cover and total grass cover were both influential in 9% of the predictive equations, while standing crop and mulch were both in 4.5%. They concluded that decreased sediment production could be expected in ecosystems where more favourable vegetation and soil conditions exist.

Mccalla II *et al.* (1984) found that sediment production was consistently less in bunchgrass plots than sodgrass plots under short duration grazing, heavy continuous grazing, and moderate continuous grazing. Heavy sediment loss from heavy continuous grazing was attributed to small amounts of bunchgrass present. Bunchgrass cover accounted for 28% of the variation in sediment production and was an important variable compared to sodgrass and forb cover that only accounted for 2% of the variation. Sodgrass and forb cover were positively related to sediment loss.

Low plant biomass production occasioned by high runoff rates (Kironchi 1998) and high soil loss rates (Nyaoro 1996) leads to degradation of semiarid grazing lands and low livestock productivity. This calls for the need to determine the role of various vegetation cover types in water distribution within grazing ecosystems (Liniger and Thomas 1998) and management solutions that target improving grass cover as a basis of restoring the primary productivity of arid and semiarid areas. Also, degradation of grazing lands can be attributed to overgrazing occasioned by inappropriate land tenure (Pratt and Gwynne 1977, Herren 1990). Therefore, there is need to adopt land tenure systems that are responsive to the needs of vegetation and the production system.

The sections that follow review the connectivity between land tenure, environmental security and livestock productivity. Also, concepts of land tenure and land tenure transformations in the drylands are presented. The section concludes on opportunities for adjusting land tenure arrangements to facilitate access and extraction of grazing resources for sustainable livestock production in land-limited production systems.

2.9. GRAZING LAND TENURE, SYSTEM STABILITY AND LIVESTOCK PRODUCTIVITY

In eastern Africa aridity increases from the south to the north, following declining rainfall regimes from the equatorial belt. This aridity gradient in combination with diverse landforms has given rise to diverse vegetation types that are sparsely and unevenly distributed in space and time. These distribution patterns of grazing resources have, in part, dictated the types of animals kept and the modes of resource exploitation patterns. A multispecies mix of animals kept, mainly camels, cattle, sheep and goats, largely depends on highly mobile, opportunistic and tracking grazing strategies (Sandford 1983, Ellis and Swift 1988, Behnke and Scoones 1993, Galaty 1994).

Attendant to resource use, land tenure systems and traditional resource management institutional frameworks have evolved to govern land ownership, resource control, access and use. Land tenure refers to the terms and conditions on which natural resources are held and used (Bruce 1986). That is, it defines the property ownership rights relations that are sanctioned by individuals and the wider society in which they live (Lane and Moorehead 1994, Lane 1998). Property in this case represents a claim to a benefit stream that some higher authority will agree to protect. Dryland resources in eastern Africa are, by and large, owned under three controlled access property regimes: state, communal, and private property.

Communal tenure that is widespread in the drylands has evolved out of necessity. Drylands are characterized by high fluctuations in grazing resource distribution and production, necessitating herding strategies to be highly mobile and flexible. In tandem, the herding communities have adopted communal tenure systems that facilitate general claims over large grazing territories, with more specific ownership over water sources and fodder trees (Lane 1998, Hendrickson *et al.* 1998). That is, in the drylands, herders have adopted highly flexible tenure systems and strategies over time as the most efficient means of exploiting transient water and grazing resources.

These resource use patterns are based upon risk spreading and flexible mechanisms such as mobility, communal land ownership, large herd sizes that are diversified, as well as herd separation and splitting. This is accompanied by complex social security networks based on kinship, friendship and patronage (Hendrickson *et al.* 1998). The herders control both the dry and wet season grazing areas that they exploit seasonally. For example, The Maasai of eastern Africa (Sperling and Galaty 1990), the Karimojong of Uganda (Ocan 1994), the Rendille and Somali of southern Wajir in Kenya (Farah 1996), and the Turkana of Kenya (Hendrickson *et al.* 1998). Others only exercise seasonal rights to grazing resources, like the Fulani of the Sahel (Grayzel 1990).

In all these cases, rights to resources accrue to families by virtue of their affiliation to the community by descent (Galaty 1994). Mobility provides the means of accessing the resources while communal ownership is a prerequisite for mobility. In this sense, the pastoral management strategies are aimed at exploiting multiple vegetation states at the landscape level (Oba *et al.* 2000), with mobility ensuring that resources are utilized at their peak productivity. In more settled settings, there is concrete and specific territorial claims, particularly claims to wet and dry season grazing areas. However, such territorial claims are not entirely exclusive, but allow for overlapping claims on resource control and use.

Grazing resource use strategies based on communal land tenure have in the past realized high livestock productivities. Breman and de Wit (1983) observed that traditional livestock systems in semiarid Africa could yield up to ten times more protein per hectare than ranching in comparable regions of the United States or Australia. Also, such high productivities are achieved at low cost compared to the intensive fossil-energy based systems (Saleem 1998). Furthermore, herders can obtain 2.5 times more energy from combined meat and milk off-take than from meat alone. Thus, herders' strategy of using a broad array of animal species to exploit different forage types under flexible land tenure maximizes output per unit area.

The seemingly viable and productive traditional systems have increasingly become subjected to a number of factors that undermine their sustainability. This has been mainly through increasing population of cultivators and expanding patterns of cultivation into key grazing lands; annexing grazing lands to create national parks and game reserves; privatization and exclusivity of use of grazing lands; rapid commercialization and modernization of herder's economies and attendant disintegration of traditional structures controlling resource use and access; and pre- and post-independence government policies that favoured sedentarization and crop farming. This has intensified land tenure conflicts particularly between herders and cultivators (Hussein 1998) with respect to access to and control over land, access to rare and seasonal water resources, and access to dry season grazing areas. The net effect of these factors and conflicts has been diminished grazing lands and reduced mobility of herds, leading to declining productivity of livestock in the drylands (Saleem 1998, Turner 1999). In addition to this, today, herders are increasingly finding it difficult to cope with their livelihoods as a result of their population pressure relative to available resources, and worsening climatic conditions particularly declining amounts of rainfall and associated recurrent and persistent droughts.

As a consequence, in the last two decades, large populations of herding communities in sub-Saharan Africa and eastern Africa in particular, have faced and continue to be faced with problems of degradation of land-based resources, high vulnerability to droughts, famine and food insecurity. This saw the international community under the United Nations Rio de Janeiro Conference on Environment and Development (UNCED 1992) formally recognize the dryland peoples' dilemma. Subsequently, the Convention to Combat Desertification (UNCCD 1994) was born, laying out broad frameworks and mechanisms for addressing these problems. However, bedeviled by past unsuccessful interventions in dryland management and livestock development in Africa, action from within and without has been slow. Yet, this crisis of environmental and livelihood insecurity in the drylands has continued to intensify.

Underlying the environmental degradation crisis is the inadequate understanding of dryland ecology (Ellis and Swift 1988, Oba *et al.* 2000) and misunderstanding of traditional herders' land tenure systems (sandford 1983, Galaty 1994). This has forced a number of both natural and social scientists to call for a shift in paradigms both at the ecological and social levels (Hjort 1992, Behnke and Scoones 1993, Oba *et al.* 2000) as a basis of refocusing dryland resource management. Also, case specific research is needed to create greater understanding of dryland ecology, emerging land tenure systems and attendant institutions to enhance resource management and livestock productivity.

2.9.1. Concepts of land tenure in the drylands

Three concepts have mainly informed the thinking of land tenure in the whole of eastern Africa and the drylands in particular:

1. Hardin's 'Tragedy of the Commons' theory (1968). According to this theory, herders own their animals individually, while the range they exploit is open access, that is, the pastures used belong to nobody. Therefore, herders rationally pursue strategies to maximize personal gains through increasing animal numbers since the incremental costs of an extra animal are shared by all but benefits accrue directly and individually. This theory further assumes that restraint by one herder does not dissuade the others from exploiting the pastures. As a consequence, all the herders pursue the same strategy, of investing in more animals that with time overgraze and degrade the range. Hence, a tragedy occurs. This argument derives from the game theory, which advances that if two competing users of a public good have a choice between conserving or depleting a resource, they will both choose to deplete the resource as ones restraint will be exploited by the other. Thus, this concept depicts traditional herders to be incapable of collectively undertaking sustainable range use, and have no adequate institutions to regulate the use

of grazing resources. Consequently, the 'Tragedy of the Commons' argument has been used to condemn herders' traditional tenure systems as inefficient, requiring drastic and fast reforms to reverse negative trends in resource use. Reforming the traditional tenure aims at enhancing the efficiency of resource use by internalizing the costs of resource exploitation to bear directly on users (Behnke 1985). This has led to concerted efforts to privatize, title, and in most cases individualize land and resource ownership through individual tenure or various forms of group tenure (Helland 1990, Hussein 1998) by governments in dryland Africa without due regard to and close scrutiny of existing traditional tenure systems.

2. The property rights school. This school of thought argues that as resources become scarcer and acquire greater value, they will increasingly become controlled. In tandem with this, institutional frameworks for resource control and use will develop that shifts tenure regimes from open to private access, with exclusive rights of use (Behnke 1985). That is, shifts from open to private property rights occur as the benefits of controlling a resource exceed the costs of policing it, with the right for exclusive use providing the incentive for investment (Lane and Moorehead 1994).

3. The assurance problem. This theory presents a counter argument on the game theory. It assumes that where expectations, assurance and actions can be coordinated, herders pursue cooperative behaviour as a utility maximizing strategy. As a consequence, herders will respect rules governing resource allocation and use. This gives way, with time, for institutions and sustainable resource management systems to intrinsically develop among the herders. That is, a common property resource management regime develops, which is characterized by a community of users; a body of rules governing use rights, exchange rights, and distribution of entitlements; and management subsystems and authority instruments (Bromley and Cernea 1989). The users exclude outsiders from using their resources and adherence to the management system ensures that the tragedy of the commons does not occur. Under this system of controlled access, communal property becomes undermined by external factors that inhibit coordination of the herders' action

(Lane and Moorehead 1994, Lane 1998). In particular, imposing unsuitable land tenure legislation and policies that emphasize sedentarisation, and privatization of tenure systems are cited (Ndagala 1994, Galaty 1994a) to have contributed greatly to the breakdown of customary tenure in dryland eastern Africa. Consequently, overgrazing and resource degradation have occurred.

The property rights school and the assurance problem concepts attest to the natural instincts of man of controlling resources and regulating their use. They embody man's pursuits to impose various levels of control and use of resources as necessary. These concepts also recognize the critical role of resources in sustaining human life. This places a heavy responsibility on man to use resources wisely. These concepts are therefore in line with what all societies have tried to do over time, using resources prudently for the sake of humanity. The tragedy of the commons theory premises portends self-destruction, and is thus, unlikely to be adopted, given the inherent survival instincts in all living things, including man.

2.9.2. Land tenure transformations in the drylands of eastern Africa with special reference to Kenya

Informed by their physical environment, herders in eastern Africa have over time developed and adopted an intricate controlled access, communal property regime. Under this property regime, rights to resources accrue to groups of individuals, or families by virtue of their affiliation to the community by lineage or descent. Access and control of resources is by the community and encroachment by outsiders is strongly resisted. The community exploits a large spatial scale and communal land tenure provides the necessary flexibility for effective and rapid exploitation of transient pasture resources (Galaty 1994, Farah 1996). This opportunistic, mobile resource exploitation strategy necessitated decision making to be highly decentralized and centered on the herding groups (sandford 1983). This pastoral resource management and exploitation strategy refined over time fitted harmoniously with the ecology of the dryland ecosystems.

In spite of the above scenario of herders eking a living by applying tenure systems and resource exploitation strategies that are adaptive, a number of factors acting singly or in combination have undermined and threatened the sustainability of their production systems. These include the colonial and post-colonial government policies that focused on land alienation and privatization.

Under the colonial rule, land in the hands of the herding communities of eastern Africa was considered unowned or underutilized. The colonial governments under pressure to secure land for commercial agriculture and wildlife conservation annexed large tracts of the grazing lands. As Kituyi (1998) put it, the colonial government by signing treaties between 1904 and 1913 saw the Maasai of Kenya losing up to 50% of their land to colonial settlers. Other unoccupied lands were declared Crown Land that opened up to indiscriminate appropriation by post-independent government to create game sanctuaries and forest reserves. In Uganda, the Crown Lands Ordinance of 1913 empowered the British colonial authority to alienate freehold land under the control of the Africans (Kisamba-Mugerwa 1998). The colonial government then encouraged settled agriculture for cash crops under individual private freehold title. Similar patterns followed in Tanzania under the German Imperial Ordinance of 1895 and the British Land Ordinance of 1923 (Ndagala 1998).

Post-independent governments of eastern Africa, informed by Hardin's tragedy of the commons theory (Hardin 1968), assumed communal systems of property ownership to lead to inefficient resource exploitation, overgrazing and resource degradation, low productivity in terms of livestock off-takes, and low levels of investments. The cattle complex proposition put forward by Herskovits in 1926 reinforced this position. That is, traditional herders accumulated livestock numbers for prestige but not for practical reasons. These misconceptions and prejudices were held, in spite of herders keeping livestock as storage of value and insurance against a wide range of risks (Ndagala 1994). Also, there was no proper accounting of externalities that impacted negatively on the herders' systems, mainly loss of grazing land to other land uses, thus forcing herders to crowd and overgraze the remaining smaller areas (Hjort 1982), and breakdown of traditional institutions for regulating resource use (Glantz 1977).

For the agropastoral systems, the important role of different livestock in optimizing resource use and enhancing sustainability of the production systems (Schiere *et al.* 2002) were ignored. Furthermore, as Ndagala (1994) noted, the wandering and random nature of herders' resource exploitation strategies created the impression that herders' claim to particular parcels of land was fluid and temporary. Thus, faced with the need to accelerate economic growth and development, the post-independent governments have pursued land use policies that in one way or the other are geared to reforming the traditional communal land tenure.

In reforming the traditional land tenure, governments have sought to internalize costs and benefits of resource users. This reform strategy is pegged on environmental economic theory that according to Wachter (1992) calls for property rights to be: completely specified to serve as a perfect system of information about the rights that accompany ownership; exclusive to ensure that benefits accrue and costs bear directly to persons using a resource; transferable to ensure that rights gravitate to their highest-value use; and enforceable and completely enforced. To this end, two main processes with profound impacts on the sustainability of herders' production systems have been pursued relentlessly throughout the eastern African drylands: sedentarization of the herders and privatization of the range.

Sedentarization, seen as a means of transforming the herders' traditional production systems (Ndagala 1994), aims at confining herders and their livestock within discrete administrative units, followed by titling and privatization. As Xavier (1997) wrote, titling and privatization were assumed to enhance tenure security, transferability of ownership, increased land investments by using titles as collateral to secure credit, and thus, lead to resource allocation efficiency and increased productivity. In this sense, as noted by Besteman (1994), land tenure is seen as an economic tool that can be used to obtain desired economic results. That is, tenure reforms are a basis for more investments and capital intensification. Thus, the role played by land tenure to secure livelihoods at the subsistence level of production is ignored and reforms are pursued to meet the capitalistic interest.

This reform agenda does not only draw from the colonial legacy, but in recent times is driven by the wave of western capitalism spearheaded by the World Bank and the International Monetary Fund (IMF). Toulmin and Pepper (2000) observed that western countries including the World Bank see land reform in Africa in terms of ensuring sufficient security of tenure to encourage agricultural investment, reduce land conflicts, allocate land from less to more productive users, and open up African countries to outside investment in agriculture.

How far these land reforms have succeeded remains debatable. Evidence available from the drylands of eastern Africa (Ndagala 1994, Galaty 1994a, Bazaara 1994), reveals that effected land reforms have, by and large, contributed to the dispossession and marginalization of herders from the mainstream national economies. The failure of land privatization is attributed to inept transfer of schemes used in densely populated regions of intensified cultivation to the sparsely populated drylands (Galaty 1999), whose ecologies dictate flexible land rights that can effectively allow the exploitation of dispersed and seasonal range resources.

In Kenya, for example, land reforms began during the colonial period. The British colonial government faced with, the Mau Mau rebellion, for land by the inhabitants, sought to undermine and suppress the rebellion by undertaking land reforms aimed at enhancing agricultural growth in the native reserves. Accordingly, the colonial government adopted the Swynnerton plan of 1954 that aimed at replacing indigenous land tenure systems with a system that entrenched property rights similar to what the English law provided (Kanyinga 1997, Wanjala 2000). The process began by identifying individual rights in land scattered over different places. The pieces of land were then recorded, demarcated and adjudicated. This was followed by land consolidation into single units. The consolidated units were registered, titled and allocated to single individuals, particularly heads of the nucleus family. Therefore, individual land ownership with exclusive rights is a colonial legacy and is to date pursued with increasing intensity even in dry areas where such form of ownership is unsustainable with respect to sound resource use.

The spread of land individualization to the drylands of Kenya is also partly motivated by earlier arguments in the Swynnerton plan, that security of tenure provided by title will allow land owners to use it as collateral for securing development capital so as to enhance investments in land, leading to increased productivity. Evidence available suggests the contrary. Pinckney and Kimuyu (1994) observed that titling had little effect on investments or credit markets. They observed that in Kenya, titling had not increased land-secured credit as there were no effective rural financial institutions, and lenders would, in case of default on credit loans, find it difficult to redeem the collateral. That is, lenders would find it difficult to foreclose on land used as collateral in rural settings where one outside the customary lineage is not allowed to buy land. Furthermore, title deeds did not give the title-holders complete rights of transferability, as witnessed by a number of litigation when members of the lineage are disinherited (Galaty 1994a, Pinckney and Kimuyu 1994).

The land reform process of individualization, titling and registration has intensified over time. Unfortunately, it has greatly contributed to increased concentration of land in the hands of a few, particularly the elite through questionable modes of allocation. This has had the greatest impact in the drylands where prime lands have been taken away from the traditional production system and concentrated on the hands of the rich (Fratkin 1994, Leach 2000). Yet, the national states quietly sanction such outcomes, as land given to the elite and rich of society is neither for purposes of economic development nor for development of indigenous capital, but principally for purposes of maintaining patronage and political loyalty (Kanyimba 1997, Galaty 1999, Klopp 2000).

Such trends of individuation and removal of prime land from mainstream production continue to threaten the livelihoods of the poor, especially those highly dependent on subsistence farming. This happens because the two processes bear directly on aspects related to land productivity. Individualization and subsequent subdivisions of land directly reduces ratios of land per person and economies of scale. Land alienation for other purposes directly removes productive land from production and deprives the needy of access to a key production resource.

2.9.3. Land tenure and modernization of traditional livestock systems

Attempts to address the land problems of the herding communities in eastern Africa remain a sensitive issue. Also, efforts to modernize the livestock sector in the drylands, while maintaining the traditional systems of the herders, through well-intended development models have failed (Galaty 1994a, McCarthy and Swallow 1999). The introduction of the group ranch concept in the drylands of eastern Africa provides a good example of such attempts.

The group ranching model was first tried out in Kenya. Provided for in the Group Land (Representatives) Act of 1968, it was envisioned to be a system that would enhance modernization of livestock production, protect the land for the local community from outsiders, and maintain the traditional ways of life of the herders (Keya 1991, Leach 2000). The herders were grouped into large traditional organizational units within given physical boundaries. The group ranches ranged in size from 100,000-200,000 acres in the drier, less populated areas to 10,000-20,000 acres in the higher potential and more populated areas. The group ranch model aimed at securing land rights for the herders through registration and titling of the ranch; provide an economically secure basis for investment in ranch development with land titles being used as collateral to secure development loans; and in the long-term make the land responsive to market forces (Galaty 1994a).

To activate the model, the government and donors financed the project to provide facilities such as water developments (boreholes), disease control, credit, and marketing services. Along side, individual ranches of progressive ranchers were established to act as models for the group ranches. The success of the model was short-lived. As noted by Keya (1991) and Galaty (1994a), a wave of droughts forced the ranchers to move outside their boundaries in search of pastures. Boreholes were left unattended, piping systems were vandalized, and loans given out were not serviced. Also, as time went by, those with influence sought to demarcate individual portions within the group to create individual ranches and acquire own titles. This gave such individuals double advantage, having private land from which other community members were excluded and yet retaining access to the common resources of the group ranch (Galaty 1994a). Later, as the human population in the group ranch increased and second-generation members sought registration, social friction ensued. The group ranches failed and sub-division to individual units started in earnest, without regard to whether the smaller units were economically viable.

Sub-division of the group ranches and individuation with exclusive rights of use has led to the collapse of the herders' production system as seen in the southern rangelands of Kenya. As Galaty (1994b, 1999) points out, during the sub-division, many outsiders were included who quickly sold out their pieces of land to speculators. The speculators quickly acquired loans using the titles as collateral to invest elsewhere. In other cases, some of the individual ranchers sold the land to avoid foreclosure and auctioning following earlier loans acquired to develop individual ranch infrastructure – fences, boreholes and upgrading of the herds, or purchase of young stock for fattening and sale. In this process, it is the poor of the poor herders who lost out in terms of land, resources and livelihoods. Therefore, attempts to reform customary land tenure to individual private tenure solely to enhance tenure security, increase investments in land, increase productivity, and make land more responsive to markets have not been realized. These attempts have by and large undermined a viable and working system particularly for the herding communities of eastern Africa.

Customary tenure, as Besteman (1994) observed, is highly adaptive to land use needs and micro-ecological circumstances, highly flexible to changing socio-economic and demographic contexts, and responsive to pressures for investments and land transfers. Also, belonging to and maintaining social relations in a community assured tenure security. Moreover, in other cases, customary tenure provided for individual ownership of resources like fodder trees and smallholding pastures near homesteads. Holding scattered parcels of land by different groups and individuals was a risk spreading strategy in harsh environments. Indeed, as Lund (2000) asserted, land privatization has often constrained the customary practice and hampered land tenure security.

2.9.4. Implications and opportunities for meeting land tenure challenges

In rural areas of eastern Africa, customary laws still prevail in sorting out land use conflicts and inheritance (Seppala 1991). For example, Haugerud (1989) found that land holdings presented by the land registry in Kenya bore little resemblance to patterns of land use in rural areas. Customary tenure continued to govern patterns of lending, borrowing, sub-division, sales and succession. Also, customary institutions like the council of elders continue to play an important role in managing, regulating and supervising users of common resources in most of the subsistence systems of Africa (Bonnet 2000). There is also widespread use of secondary (derived) rights on resources. It is the use of secondary rights, operating under less secure conditions that give flexibility to rigid individual property rights (Besteman 1994).

Writing on land rights, Delville *et al.* (2001) observed that the diversity and flexibility of secondary rights stem from particular needs of a farming system. Secondary rights are important in allocating production factors in changing circumstances of production systems and in assisting producers to maintain production when their lands are not in production. However, attempts to regulate them within a restrictive framework impedes their evolution and may lead to the inability of farming systems to adjust to changing asset availability and economic productivity. Furthermore, secondary rights may be abused, resulting in negative impacts on land resources. For example, short-term borrowers of land may tend to maximize production at the expense of resource conservation. Delinking lands, which are borrowed at some point, from private ownership will facilitate the emergence of co-management among users, leading to resource conservation (Thebaud 1995).

Since unattenuated customary tenure systems may not be restored in the eastern African drylands, then responsive tenure arrangements must be put in place to enhance resource utilization, productivity and integrity for secure livelihoods. Establishing statutory individual exclusive rights of tenure over land based resources in the drylands of eastern Africa has seriously undermined the ability of herding communities to access key grazing resources that are discontinuous and sparsely distributed. This has contributed to herders who, by and large, rely on livestock for their livelihoods becoming highly vulnerable to famine, droughts and food insecurity. This situation is aggravated by large losses of productive land from the herding communities to outsiders and other sectors, mainly farming, forestry and wildlife.

Customary tenure and traditional institutions for resource control, access, utilization, and management though fairly efficient and sustainable have been marginalized. Also, the adoption of a mono-tenure model across the diverse ecologies of the drylands has defeated the essence of matching forms of land holding with land use. The combined effect of these factors has led to a once thriving livestock sub-sector in the eastern Africa drylands to increasingly lose ground and sustainability. To reverse these trends may not be an easy task. However, customary tenure and traditional institutions with a compatible mix of formal systems of resource management may present a starting point for designing sustainable land tenure and resource management systems. Of particular significance, tenure systems modelled along controlled customary tenure together with a range of secondary rights may provide the opportunity of meeting the challenges of resource management and sustainable livestock production in these areas.

The Kamba agropastoral system reported herein evolved as a slash and burn-bush fallowing system around a settled base (Tiffen 1992). Cultivation gave claim to the land according to the Kamba custom. The livestock grazed anywhere. However, with increasing population pressure and expanding patterns of cropping, the area for grazing per household has become smaller and more exclusive. These trends, accompanied by increasing incidences of adverse climatic conditions, have threatened the sustainability of livestock keeping. This calls for more research to clarify the limitations imposed by tenure systems on livestock production and guide the development of tenure strategies that are more responsive to new scenarios in the production system for enhanced livestock productivity. Therefore, the grazing land tenure systems of the Kamba agropastoralists were analyzed in this to address the following issues: modes of land ownership; grazing resource control, access and use; and roles and enforcement of secondary rights in the production system.

2.10. LIVESTOCK PRODUCTIVITY AND ECOSYSTEM STABILITY MODELS

The effects of the any change in natural ecosystems that influence biological productivity are understood to various degrees. However, it is not feasible to know the impacts of all factors that affect biological productivity. Yet, it is important to estimate the levels and know the modes of interaction of various factors to realize set production goals or meet future production goals. Mathematical models are important tools that can be used to integrate the ecological, sociological, and economic relationships and suggest outcomes of decisions being considered (Boone *et al.* 2000).

A number of livestock productivity models have been developed in recent years (MacNeil and Harris 1988, Korver and Van Arendonk 1988). A number of them are widely and sufficiently documented for direct use. For example, the Texas A & M University Sheep and Goat Simulation model (Blackburne *et al.* 1987) sets seasonal feed availability, feed quality and worm load to determine survival, yields and reproductive performance of a given genotype. HerdEcon model (Stafford Smith *et al.* 1988) is a cash flow and financial assessment model applied to beef cattle and sheep ranches. The ILCA Bioeconomic Herd model (von Kaufmann *et al.* 1990) is a cost-benefit analysis adopted to cattle herds.

The models available for energy flow studies and productivity estimates include: PRY model (Baptist 1990) that is a herd and flock productivity assessment model; Savanna model (Boone *et al.* 2000) that is under validation is an integrated management and assessment model for balancing food security, conservation and ecosystem integrity in East Africa; and Phytomas Growth Simulator model (PHYGROW) (Rowan 1995) which simulates daily stocking rates based on daily total forage available. This last one has been validated and currently is being applied to develop indicators for livestock early warning systems (GL-CRSP LEWS 2000). In the current study, mathematical models that estimate forage production rates and livestock forage consumption rates were applied to predict system stability (Noymeir 1975, 1978, Ungar and Noymeir 1988).

CHAPTER THREE

MATERIALS AND METHODS

3.1. LOCATION OF STUDY AREA

Figure 3.1. The location of Kibwezi Division in Kenya and areas sampled

KENYA ASAL DISTRICTS

SAMPLED AREAS IN KIBWEZI DIVISION, MAKUENI DISTRICT.

This study was conducted in Kibwezi Division of Makueni District (Figure 3.1). The district covers about 7,263 sq. km (ROK 1994c), and lies between 1.5^0-3^{0}S and 37^0-38.5^{0}E. It is bordered by Kitui District to the east, Taita District to the south, Kajiado District to the west and Machakos District to the north. The district receives an average annual rainfall of 500mm in the lowlands in the south and 1200mm in the highlands in the north. The rainfall is characterized by small total amounts, strong seasonal and bimodal distribution, with high temporal and spatial variability between seasons and years. Annual mean temperatures range between 19^{0}C to 26^{0}C (Jaetzold and Schmidt 1983). The Kamba agropastoralists are the main inhabitants, and their mainstream economic activity is raising livestock and cultivating grains and pulses (Tiffen *et al.* 1994).

Table. 3.1. Agro-climatic zones of Makueni District, Kenya

Zone	r/EO*	Classification	Annual average rainfall (mm)	Annual average potential evapo-transpiration (mm)	Vegetation (altitude not exceeding 3,000m)	Potential for plant growth (assuming soil condition is unlimiting)	Risk of crop failure
I	>80	Humid	1100-2700	1200-2000	Moist forest	Very high	Extremely low (0-1%)
II	65-80	Sub-humid	1000-1600	1300-2100	Moist and dry forest	High	Very low (1-5%)
III	50-65	Semi-humid	800-1400	1450-2200	Dry forest and moist woodland	High to medium	Fairly low (5-10%)
IV	40-50	Semi-humid to semi-arid	600-1100	1550-2200	Dry woodland and bush land	Medium	Low (10-25%)
V	25-40	Semi-arid	450-900	1650-2300	Bush land	Medium to low	High (25-75%)
VI	15-25	Arid	300-500	1900-2400	Bush land and shrub land	Low	Very high (75-95%)
VII	<15	Very arid	150-300	2100-2500	Desert scrub	Very low	Extremely high (95-100%)

*r is annual average rainfall in mm; EO is potential annual average evaporation in mm
Source: Sombroek and Braun (1980)

Makueni District is classified into six agro-climatic zones (ACZ) (Sombroek and Braun 1980). The dominant of ones are ACZs IV and V where risks of crop failure are high (Table 3.1). According to agro-climatic zones, the district has three main soil types: AEZ UM2/LM2, covers areas with red clay on hills and lowlands, sand soils and black cotton soils; AEZ LM4/LM5, covers areas with red clay and black cotton soils; and AEZ UM3/LM3, covers areas with soils with high potential for cotton production (Jaetzold and Schmidt 1983). The natural vegetation is the dry form of woodland and savanna, with several tree species, mainly: *Acacia* spp. (A), *Commiphora africana, Adonsonia digitata* and *Tamarindus indica*. Shrubs include *A. mellifera, A. Senegal*, and *Grewia* spp. Perennial grasses include *Cenchrus ciliaris, Chloris roxburghiana, Panicum maximum, Eragrostis superba, Digitaria milanjiana* and *Enteropogon macrostachyus.*

Kibwezi Division lies in the central part of Makueni District and has an area of 3,400 sq. km. It is dry and mostly lies in ACZ IV-V. The division is characterized by rainfall regimes, and soil and vegetation similar to those found in the rest of the District. The study was conducted in zones ACZ IV and V of the division, described as low potential maize zone, and high potential livestock and millet zone; and very low potential maize zone and medium potential livestock and millet zone, respectively (Jaetzold and Schmidt 1983, ROK 1989).

3.2. LIVESTOCK GRAZING ECOLOGY AND RESOURCE EXTRACTION STUDIES

Samples consisted of three herds. Two of the herds were selected from a random sample of 50 households designated for a grazing land tenure study in the Kibwezi community and were designated as system one (S1). The third herd designated as system two (S2), was the University of Nairobi herd based at the ranch in the Institute of Dryland Research, Development and Utilization (IDRDU) field station in the area. Data on the grazing ecology of cattle, sheep and goats were collected through two wet and two dry seasons in sequence through daylong excursions across species and season. Three animals per species per herd balanced for weight and age were used to quantify food selection by the bite count method (Backer and Hobbs 1982). Forage classes, plants and plant parts selected were recorded in 10-minute feeding trials for each animal species alternately. A total of 432 feeding trials were conducted and evenly distributed across species and season. Forage classes were categorized as perennial grasses, herbaceous (annual grasses, forbs and herbs), woody shrubs and trees. The grazed sites, based on vegetation type, water bodies, and topographic features and intensity of use during the grazing period were also recorded. The intensity of use was estimated as the number of herd locations per unit area. Herd locations per unit area reflects the duration of time a herd spends in an area. Herd locations were recorded in Universal Transverse Mercator coordinates (UTM coordinates define two dimensional, horizontal positions) every 15 minutes using a hand-held global positioning system (GPS). The GPS was also used to determine the distance travelled by the animals per day. The animals were also dewormed at the beginning of the study and their liveweights taken every 30 days for one year.

Forages that comprised at least 3% of the total bites for each feeding trial were hand plucked, trying as much as possible, to simulate the plant parts and bite sizes selected by each livestock species (Baker and Hobbs 1982). Botanical compositions of diets were determined on a dry weight basis by multiplying total bites by bite weight (averaged for 25 hand-plucked samples) following procedures of Baker and Hobbs (1982). Average total grazing time per animal species per day was determined during each sampling period.

Samples of each principal forage type were collected during the feeding trials for each animal species and season, air dried in the field and taken to laboratory for determinations of Kjeldahl nitrogen concentrations (AOAC 1980), *in vitro* dry matter (IVDDM) and organic matter (DOM) digestibility according to procedures of Tilley and Terry (1963) and pressure transducer method, respectively. Neutral detergent fibre (NDF), acid detergent fibre (ADF), lignin (ADL), and ash in the forage samples were also determined by methods of Van Soest (1963a, b). Grazing time, average bite size, bite count, percent forage chemical composition and organic matter digestibility were used to derive seasonal energy extraction by the animals using equations 1 and 2 as applies to tropical forages:

Estimated metabolizable energy intake $(\text{MJ}) = \text{DOMI}(\text{kg/d}) \times 18.5 \times 0.81$ (1)

This is equivalent to:

$$(\text{MJ}) = \frac{\text{BWT} \times \text{BC} \times \text{GT} \times \text{DM\%} \times \text{DOM\%} \times 60 \times 18.5 \times 0.81}{20} \qquad (2)$$

Where BWT = bite weight, BC = number of bites, GT = grazing time per day, DM = dry matter (%),

DOMI = digestible organic matter intake, and DOM% = digestible organic matter (%).

Energy availability for production was estimated as the difference between metabolizable energy intake and energy expenditure for maintenance by the animals. Extra energy costs for feeding, walking and /or lactation were also factored in. Equations 3 to 10 that have been validated for local animal breeds were used (King 1983):

- For zebu cattle

  (i) Energy for maintenance $(\text{MJ}) = \dfrac{0.343\text{wt}^{0.73}}{0.55 + (0.3 \times 0.81 \times \text{d})}$ (3)

  Where wt =animal liveweight, d= organic matter digestibility of diet

  (ii) Energy for feeding $(\text{MJ}) = 0.04$ MEI (4)

  Where MEI = metabolizable energy intake

  (iii) Energy for walking $(\text{MJ}) = \text{wt} \times 0.0018 \times \text{distance travelled (km)}$ (5)

  (iv) Energy for lactation $(\text{MJ}) = \dfrac{3.6 \times \text{Milk yield (kg/day)}}{0.463 + (0.24 \times 0.81 \times \text{d})}$ (6)

- For sheep

  (i) Energy for maintenance $(\text{MJ}) = \dfrac{0.243\text{wt}^{0.73}}{0.55 + (0.3 \times 0.81 \times \text{d})}$ (7)

  Where wt =animal liveweight, d= organic matter digestibility of diet

  (ii) Energy for feeding $(\text{MJ}) = 0.04$ MEI

  Where MEI = metabolizable energy intake

(iii) Energy for walking (MJ) $= \mathrm{wt} \times 0.0019 \times \text{distance travelled (km)}$ (8)

$$\text{(iv) Energy for lactation (MJ)} = \frac{3.0 \times \text{milk yield (kg/day)}}{0.463 + (0.24 \times 0.81 \times d)} \qquad (9)$$

- For goats

$$\text{(i) Energy for maintenance (MJ)} = \frac{0.251\mathrm{wt}^{0.75}}{0.55 + (0.3 \times 0.81 \times d)} \qquad (10)$$

Where wt =animal liveweight, d= organic matter digestibility of diet

(ii) Energy for feeding (MJ) = 0.04 MEI

Where MEI = metabolizable energy intake

(iii) Energy for walking (MJ) $= \mathrm{wt} \times 0.0019 \times \text{distance travelled (km)}$

$$\text{(iv) Energy for lactation (MJ)} = \frac{3.0 \times \text{milk yield (kg/day)}}{0.463 + (0.24 \times 0.81 \times d)}$$

In calculating the energy cost for lactation, an absolute value of 2, 0.35 and 0.35 kilogram of milk yield per day was assumed for cattle, sheep and goats, respectively.

For a few of the common perennial grasses in the area, data were collected to determine the point at which grazing animals could optimize energy extraction. This is realized at the point where two constraint curves intersect. That is the cropping and digestive constraint curves. A cropping curve shows the maximum amount of energy an individual animal can consume in the absence of the digestive constraint, while a digestion curve shows the maximum amount of energy an individual animal can process in absence of the cropping constraint. Therefore, biweekly measurements of available sward biomass during the growing period were undertaken using 4 by 4 metre sample plots. Also, sward biomass organic matter digestibility was analyzed using the *in vitro* techniques.

Diet diversity ($\overline{H}$) was calculated seasonally on a forage class basis for each livestock species and aggregate herd using the Shannon-wiener index (Shannon 1948, Hurtubia 1973). This index is given by equation 11.

$$\overline{H} = -\sum_{i=1}^{N_i} (p_i \log p_i) \qquad (11)$$

Where N_i = number of forage classes,

P_i = proportion of the i^{th} forage class in a given diet

Seasonal niche overlap among pairs of livestock species in diet selection and habitat use was calculated using the modified Morisita index (Horn 1966). Multiplying the respective diet and habitat Morisita coefficients derives total trophic overlap. The expression is given in equation 12.

$$\hat{C}_\lambda = \frac{2\sum_{i=1}^{si} x_i y_i}{\sum_{i=1}^{s} x_i^2 + \sum_{i=1}^{s} y_i^2} \qquad (12)$$

Where $\hat{C}_\lambda$ = modified Morisita index (overlap index). The overlap index ranges from 0.0 for completely distinct diets to 1.0 for complete similarity.

S = total number of plant species

X_i and Y_i = proportion of the total diet of animal X and Y taken from the i^{th} forage class

Thus, the index becomes a diet or habitat index, if X and Y are diets or habitats being sampled.

Standing herbaceous biomass was determined by clipping $0.25m^2$ rectangular quadrats placed at intervals of 20 metres along 60m line transects. Three randomly placed line transects were used per herd location. The transects were 100m apart. The herd locations sampled accounted for at least 15% of the grazing time. Grass species present in each quadrat were clipped at 2cm above the ground, and their green weight and relative frequency determined. The amount of litter present was determined. The density of trees and shrubs was estimated by the point centered quarter method (PCQ) (Dieter and Heinz 1974, Pieper 1978) at each sampling point as follows:

$$\text{Mean distance (d)} = \frac{\text{Total distance}}{\text{Total number of all plants recorded}} \qquad (13)$$

$$\text{Total density (Number/hectare)} = \frac{10{,}000}{d^2} \qquad (14)$$

Where d^2 is the mean area per plant

$$\text{Relative density (\%)} = \frac{\text{Density of } i^{\text{th}} \text{ species}}{\text{Total density}} \times 100 \qquad (15)$$

The density of woody species that significantly contributed to the energy intake by the animals was determined by multiplying the relative density of that species by total density of all species. Relative density is the number of measurements to a species divided by the total number of measurements made in all sampling points. Cover for the important seedpod producing woody species was estimated by multiplying mean crown area by density. Area covered by seedpod producing trees/shrubs was multiplied by average seedpod production per unit tree/shrub to get total seedpod production. Live weight changes of three animals per animal species balanced for age were monitored monthly during the study period. Also, calving, kidding and lambing percentage of the species were determined.

3.3. VEGETATION, SOIL HYDROLOGIC RESPONSES AND SEDIMENT PRODUCTION STUDIES

Simulated rainfall (Young *et al.* 1972) was used to study soil hydrologic responses and sediment production of sites dominated by four perennial grasses. Infiltration capacity (mlmin^{-1}) on 0.3 x 0.3m plots with different perennial grass stubble height representing five intensities of grazing (100%, 75%, 50%, 25% and 0%) was measured using The Kamphorst Rainfall Simulator. Each simulation consisted of a rain shower of 5 minutes with an intensity of 375mlmin^{-1} (6mmmin^{-1}) (Rietkerk *et al.* 2000). This was repeated for another five minutes to ensure runoff. The simulations were run in duplicate in a grazed area and a grazing exclosure. All simulations were done when soil was near field capacity. That is, the test plots were wetted to near field capacity, covered with polythene papers for 24 hours to reduce evaporation loss and maintain uniform soil surface water content. From each plot, runoff was collected, decanted and weighed. Infiltration capacity was calculated by subtracting runoff from amount of simulated rainfall applied.

Infiltration capacity (mls) = 10(simulated rainfall intensity mlmin^{-1}) – total runoff in 10 minutes

The sediment produced was washed into storage bottles, and later filtered off and dried at 105^{0}C for 24 hrs. The amount produced was converted to sediment yield in kg/ha. This was used as an index of sheet erosion as given in equation 16.

$$\text{Sediment production}\left(\text{kg/ha}\right)=\frac{\text{Sediment produced}\times\text{area}}{\text{Plot area}} \qquad (16)$$

Disturbed soil samples taken to depths of 0 to 20cm were used to determine soil moisture, soil texture, soil organic matter, and soil aggregate stability. Soil moisture content was determined by the gravimetric method (Rowell 1994). Soil texture was determined following the hydrometer method as described by Gee and Baunder (1988). The fine fraction of soil passing through a 2mm sieve was taken for texture analysis using Bouyoucos hydrometer. The textural class was determined using the standard USDA triangle (USDA 1975). The soil organic matter content (soil carbon) was determined using the wet oxidation method of

Walkley and Black (Nelson and Sommers 1982). Soil aggregate stability was determined by wet sieving procedures as described by Hillel (1980). Disturbed soil samples were sieved through a 4mm and 2mm sieve. Soil samples passing through the 4mm were used for the analysis.

Soil core samples taken to depths of 0 to 5cm were used to determine soil bulk density and soil porosity. Bulk density was determined by the core method (Blake and Hartge 1986). Soil porosity was derived from values of bulk density as outlined by London (1991). Percent foliar cover of the grasses was determined by ocular estimates on each plot from griddled quadrats. Live standing material in each plot was harvested to 2cm above the ground and weighed for green biomass yield. Also, the amount of litter present was collected and weighed.

3.4. GRAZING SYSTEM MODEL/GROWTH-CONSUMPTION MODEL: EQUILIBRIUM PARADIGM

Based on primary production, animal type, extraction rates and intake data, a growth-consumption rate model was developed to describe the stability properties and dynamics of the system. The two processes of plant production (growth) and consumption were considered. The rate parameters defined as growth rate and consumption rate dependent on the amount of herbage available (state) were used.

The assumptions of the model were for seasonal pastures as described by Noymeir (1978). They are as follows:

1. The growth rate of green biomass is a unique function of total green biomass. That is, growth rate of green biomass is a function of total green biomass.
2. The rate of consumption of green biomass by one animal is also a unique function of total green biomass. That is, the rate of consumption of green biomass by an animal is a function of total green biomass.
3. The rate of net change in green biomass is the growth rate minus the consumption rate by a given animal population (stocking rate). That is, net available green biomass is the

green biomass production minus biomass consumption by a given animal population.

4. The end of the growing season occurs at a fixed time, which is independent of the grazing history and pasture dynamics during the season.
5. The parameters of the growth function are constant from the beginning of the growing season till its end, at which growth stops.
6. Growth rate is a ramp function of biomass minus a maintenance respiration loss rate, which is linearly proportional to biomass.
7. Consumption per animal is a ramp function of biomass.

Assumptions 4 and 5 on a finite growing season assume no variations in growth parameters within the season. Assumptions 6 and 7 specify the explicit functions for growth and consumption, in which the saturation of both processes, with respect to biomass, is abrupt rather than gradual. Also, standard figures for the model as described by Noymeir (1978) were used.

For growth rate (G), the logistic function was used to give the rate equation. Thus,

$$G = rgrV\ (1 - V / V_x) \tag{17}$$

Where G= forage growth rate (kg/ha/d)

rgr= relative growth rate (d^{-1})

V= pasture biomass (kg/ha)

V_x = maximum attainable pasture biomass

For consumption rate (I), the inverted exponential function was used to give the rate equation, thus,

$$I = I_x(1 - e^{-\frac{V - V_r}{V_s - V_r}}) \tag{18}$$

Where I = intake rate of an animal (kg/d)

I_x = maximum attainable intake rate of an animal (kg/d)

V_r = residual, ungrazable, pasture biomass (kg/ha)

V_s = shape parameter (kg/ha)

The dynamics of growth and consumption rates were examined by expressing them in similar units. This was achieved by multiplying the intake rate by the stocking rate (H, the number of animals per unit area of pasture). Thus, consumption rate (C) on an area basis is defined as

$$C = IH \qquad (19)$$

From the above, C and G have same units. Plotting the growth and consumption functions on the same axis (y axis) against pasture biomass (V), the stability of the grazing system was examined. For example, at any level of V, if G is greater, V increases; if C is greater, V decreases. Points at which the functions intersect are equilibrium points, giving stable or unstable equilibrium points. Options of attaining system stability include the introduction of the concept of deferment (D) or energy subsidies (ecological subsidies) such as the use of crop residues. Deferment or use of energy subsidies in the grazing system is intended to delay the onset of grazing in order to allow V exceed the critical stability threshold.

3.5. GRAZING LAND TENURE SYSTEM, RANGE TRENDS AND LIVELIHOOD STRATEGIES

Interviews were used to obtain information on grazing land tenure, livestock enterprises, production objectives, changes in resource use, and environmental trends in the study area from households.

3.5.1. Preparation of questionnaire

A draft questionnaire taking into account the objectives of the study was constructed before setting out to the field. Questions were dichotomous, multi-choice and/or open-ended to allow for ease of capture of the diverse issues that were being investigated, with necessary detail. The questionnaire was pre-tested in a pilot survey involving 10 households, before it was used in the main survey. The 10 households belonged to the same area of survey but were not included in the actual survey. Pre-testing ensured that the final questionnaire

(Annex 1) had relevant and appropriately phrased questions for the interviews.

3.5.2. Training field enumerators

Four enumerators with secondary level of education and experience in field survey were recruited and trained. The enumerators were from the local community and were fluent in the local language and English. Furthermore. the enumerators were selected based on their field experience. In the recent past, these enumerators had participated in field interviews, having been trained and recruited in participatory rural appraisal methods. The same enumerators were used both for the pilot and main survey.

3.5.3. Sampling procedure

The sample involved 50 households distributed in 9 out of 12 sub-locations of Kibwezi Division (CBS 1999). The nine sub-locations were selected for sampling to give the study a wide scope. The sub-locations were selected by giving them a two digit number beginning from 01 to 12. Using tables of random numbers, the first nine sub-locations were picked. By taking the main transect (road/path) cutting through each sub-location, 5 to 6 households were selected per transect per sub-location and interviewed.

During sampling, the households to be interviewed were selected as follows: Two trained field enumerators drove/cycled to the central place in each sub-location; from the centre, they walked in opposite direction using predetermined transects or existing footpaths. After about every kilometer, they chose the nearest household willing to participate in the interviews. Thus, the field enumerators walked a maximum of 2 to 3km each, to interview 5 to 6 households.

3.6. MODELLING SECONDARY LAND RIGHTS

The response to secondary land rights to alleviate grazing pressure was treated as a dichotomous variable, which took a value of one if the herder/household practised them or zero if he did not. The appropriate estimation procedure is therefore the logit or probit framework. The difference between the two is that the error term for the logit follows a logistic distribution, while that of the probit follows a normal distribution. However, the logit model is preferred because it is computationally easier. Moreover, the probit model is less flexible because it cannot be readily extended to more than one predictor variable. Also, formal inference procedures are more difficult to carry out with the probit model. In most cases the logit and probit regression models agree closely except near the asymptotes (Nector *et al.* 1996). In this study, the logit model was applied to explain the factors that determine the use or non-use of secondary land rights. Therefore, secondary land right is the response variable (Y) that is binary, taking a value of 1 or 0, with probabilities of χ and χ-1, respectively. Since the determinants of Y are multiple, Y is a Bernoulli random variable, whose logistic response function parameters are best estimated by the method of maximum likelihood.

From the simple linear regression model, where the outcome Y_i is binary taking on the value of either 0 or 1, X_i is the explanatory variable such that

$$E(Y_i) = \beta_o + \beta_i X_i + \varepsilon_i \qquad (20)$$

β_o and β_1 are unknown coefficients and ε_i is a stochastic error term. Since E (ε_i) = 0, then

$$E(Y_i) = \beta_o + \beta_i X_i \qquad (21)$$

The mean response $E(Y_i)$ as given by the response function (21) is therefore the probability that $Y_i = 1$ when the level of the predictor variable is X_i. This interpretation of the mean response applies whether the response function is a simple linear or a complex multiple regression. Also, the expected probability for Y_i is given as

$$E(Y_i) = \exp(\beta_o + \beta_i X_i)/ (1+ \exp((\beta_o + \beta_i X_i)$$

Extending the simple logistic regression model to a multiple regression model, $\beta_o + \beta_i X_i$ is replaced by $\beta_o + \beta_1 X_1 + \ldots + \beta_n X_n$

That is, $Y = \beta_o + \beta_1 X_1 + \ldots + \beta_n X_n$

The interpretation of the estimated regression coefficients in the fitted response function is not the straightforward interpretation of the slope in a linear regression model. This is because a unit increase in X varies for the logistic regression model according to the location of the starting point in the X scale. An interpretation of β_1 is found in the property of the fitted logistic function that the estimated odds $\chi/(\chi-1)$ are multiplied by $\exp(\beta_1)$ for any unit increase in X.

For purposes of interpretation of the regression coefficients, the logistic model is written in terms of the logarithm of the odds, that is, the logit is given as

$\log_e(\chi/(\chi-1)) = \log_e$ (prob(household practicing secondary land rights)/ 1- prob (household practicing secondary land rights)) (22)

From equation (22), the logistic coefficient can be represented as the change in the log odds associated with a one-unit change in the independent variable. Thus, when the value of a variable changes from zero to one, and the values of the other independent variables remain unchanged, the change in the log odds of the dependent variable is given by the coefficient of the independent variable in question. Since it is easier to think of odds than the log odds, the equation in (22) is usually expressed as

$$E^y = e^{\beta 0} e^{\beta 1X1} \ldots e^{\beta nXn} \qquad (23)$$

Equation (23) is used to estimate the secondary land rights parameters. The value $e^{\beta j}$ is the factor by which the odds change when the j^th independent variable increases by one unit. It means that the odds are increased when β_j is positive, and decreased when β_j is negative. Otherwise, the $\exp(\beta)$ is the odds ratio, which estimates the chances of success with a unit change in the predictor variables (X).

Table 3.2 gives a summary of the hypothesized explanatory variables tested that influence practising of secondary land rights.

Table 3.2. Summary definitions of variables tested

Variable	Definition
FS	Farm size per household
FS/AE	Farm size per adult equivalent in the household
GA	Grazing area per household
CROP	Crop area per household
TLU/AE	Tropical livestock unit (equals to 250 kg) per adult equivalent
TLU/HH	Tropical livestock units per household
AGE(1)	Age of household head (31-40 years) (yes=1, no=0)
AGE(2)	Age of household head (41-50 years) (yes=1, no=0)
AGE (3)	Age of household head (≥51 years) (yes=1, no=0)
LEDU	Level of education attained by household head
LEDU (1)	Up to primary level of education (yes=1, no=0)
LEDU (2)	Secondary level of education (yes=1, no=0)
LEDU (3)	College level of education (yes=1, no=0)
SHOATS:COW	Number of goat and sheep to cows ratio
GA/AE	Grazing area per adult equivalent in the household
RES	Crop residue available for feeding animals
GENDER	Gender (female=0, male= 1)
SR	Stocking rate in acre per tropical livestock unit*
AE	Adult equivalent (Children of 16 years = 0.5 adult equivalent)

*1 shoat=0.14 TLUs

3.7. DATA ANALYSIS

The effects of livestock species and season on both diet composition and diet diversity were analyzed using a two-way analysis of variance. The least square difference (L.S.D) procedure was used to determine significant differences at the 0.05 level of probability (Steel and Torrie 1980). Seasonal intensity of use of different patches/sites was compared using descriptive statistics. The primary pathways of energy flow that sustain livestock productivity were described. A growth-consumption rate model was used to describe the stability properties and dynamics of the grazing system.

A logistic regression analysis was used to determine the most important factors influencing infiltration capacity and sediment production. Skewness and Kurtosis tests were applied to each variable to determine the normality of data (Snedecor and Cochran 1971). A two-way analysis of variance was then conducted to determine the effects of grass type and stubble height (level of utilization) on infiltration capacity and sediment production. Descriptive statistics were used to describe trends in the grazing environment and livelihood strategies. The secondary land rights model was executed using the SPSS 11.6 statistical package and the significance of the results tested using the Wald test (W), one of the tests suited to dealing with both linear and non-linear regression models.

CHAPTER FOUR: RESULTS AND DISCUSSION

GRAZING PATTERNS, ENERGY EXTRACTION AND SYSTEM STABILITY

4.1. VEGETATION CHARACTERISTICS

The relative frequency (%) and standing biomass (DM) of herbaceous plants in the study sites are presented in Tables 4.1, 4.2 and 4.3.

Table 4.1. Relative frequency and standing biomass of herbaceous plant species during the wet and dry seasons in site A

Plant species	Relative frequency				Standing biomass (DM) (gm^{-2})			
	Mid wet*	Late wet	Mid dry	Late dry	Mid wet	Late wet	Mid dry	Late dry
Perennial grasses								
Panicum maximum	48.5	45.3	43.0	50.9	193.2	70.4	269.6	293.6
Eragrostis superba	27.8	31.9	16.6	22.2	175.2	136.0	128.8	213.2
Eragrostis caesalpitosa	2.7	4.6	3.9	2.7	170.0	195.2	235.2	31.6
Enteropogon macrostachyus	23.6	25.5	19.4	27.8	167.2	73.6	198.4	124.4
Digitaria milanjiana	6.9	10.2	5.5	12.5	108.4	60.0	125.2	207.2
Cynodon plectostachyus	8.3	8.3	5.5	8.3	174.8	225.2	290.0	516.8
Cynodon dactylon	-	1.4	-	-	-	10.0	-	-
Heteropogon contortus	2.7	2.8	4.1	6.9	240.0	70.0	166.0	266.8
Chloris roxyburghiana	1.4	5.1	2.7	8.3	10.0	104.0	36.8	120.0
Annuals	34.6	39.3	65.2	50.0	62.0	86.8	78.8	97.6
Forbs								
Justicia flava	1.4	-	-	-	58.0	-	-	-
Tephrosia villosa	4.2	3.7	1.4	5.5	60.0	126.0	5.2	160.0
Pavonia patens	-	5.6	-	2.7	-	63.2	-	180.0
Other forbs	45.8	39.3	77.3	73.6	91.2	103.6	101.6	118.8
Total					**1510.0**	**1324.0**	**1635.6**	**2330.0**

*Mid wet season (April and November), late wet season (May and December), mid dry season (February and August), and late dry (March and October)

In site A, perennial grasses were the most abundant, accounting for 82, 71, 88, and 76% of the standing biomass in mid wet, late wet, mid dry and late dry season, respectively. Forbs followed with 14, 22, 7, and 20% of the standing biomass. Annuals accounted for less than 7% of the standing biomass across the seasons.

Table 4.2. Relative frequency and standing biomass of herbaceous plant species during the wet and dry seasons in site B

Plant species	Relative frequency				Standing biomass (DM)(gm^{-2})			
	Mid wet	Late wet	Mid dry	Late dry	Mid wet	Late wet	Mid dry	Late dry
Perennial grasses								
Panicum maximum	-	1.9	-	5.6	-	40.0	-	43.2
Eragrostis superba	7.4	7.4	13.0	11.1	80.0	30.8	65.2	175.2
Eragrostis caesalpitosa	5.6	1.9	1.9	3.7	60.0	4.0	10.0	44.0
Enteropogon macrostachyus	22.2	18.5	33.3	20.4	113.2	33.6	74.0	173.2
Digitaria milanjiana	16.7	14.8	14.8	17.4	66.0	24.4	88.8	61.6
Cenchrus ciliaris	3.7	-	1.9	-	20.0	-	50.0	-
Latipes senegalensis	-	1.9	1.9	3.7	-	10.0	10.0	60.0
Echinochloa haploclada	-	-	1.9	-	-	-	20.0	-
Chloris roxyburghiana	-	-	1.9	1.9	-	-	70.0	20.0
Annuals	66.8	53.7	74.0	83.3	66.0	27.6	40.8	106.8
Forbs								
Tephrosia villosa	9.3	5.6	1.9	3.7	72.0	76.0	20.0	55.2
Pavonia patens	1.9	3.7	-	9.3	70.0	18.0	-	173.2
Other forbs	62.9	42.4	72.2	70.3	115.2	78.8	60.4	154.0
Total					**662.4**	**343.2**	**509.2**	**1066.4**

Perennial grasses in site B accounted for 52, 42, 76 and 54% of standing biomass, in mid wet, late wet, mid dry and late dry seasons, respectively. Forbs followed closely at 39, 50, 16 and 36% across seasons. Annuals remained least abundant, accounting for less than 10% of the standing biomass across seasons.

Table 4.3. Relative frequency and standing biomass of herbaceous plant species during the wet and dry seasons in site C

Plant species	Relative frequency				Standing biomass (DM)(gm^{-2})			
	Mid wet	Late wet	Mid dry	Late dry	Mid wet	Late wet	Mid dry	Late dry
Perennial grasses								
Panicum maximum	-	1.9	-	1.9	-	10.0	-	20.0
Eragrostis superba	20.4	9.3	11.1	5.6	113.2	31.2	89.2	63.2
Heteropogon contortus	-	1.9	1.9	3.7	-	10.0	10.0	35.2
Enteropogon macrostachyus	22.2	27.8	29.6	24.1	78.4	70.8	61.6	74.0
Cynodon plectostachyus	-	1.9	1.9	-	-	50.0	30.0	-
Cenchrus ciliaris	7.4	13.0	9.3	11.1	145.2	50.8	70.0	107.6
Chloris roxyburghiana	1.9	5.6	5.6	7.4	50.0	30.8	55.2	75.2
Annuals	90.7	64.8	55.7	81.4	75.2	30.0	204.4	87.2
Forbs								
Tephrosia villosa	5.6	-	3.7	9.3	56.8	-	55.2	161.6
Pavonia patens	-	-	-	5.6	-	-	-	115.2
Sida ovata	1.9	-	3.7	7.4	90.0	-	50.0	116.8
Other forbs	47.8	33.3	46.3	90.7	91.6	54.8	89.6	164.8
Total					**700.4**	**338.4**	**715.2**	**1020.8**

As in the other sites, perennial grasses remained the most abundant, followed by forbs in site C. Perennial grasses accounted for 55, 75, 44, and 37% of standing biomass in mid wet, late wet, mid dry and late dry seasons, respectively. Forbs followed with 34, 16, 27 and 55% across seasons. The annuals recorded low standing biomass of less than 11% in all seasons except mid dry season (29%).

Total standing biomass was significantly higher in the mid wet than in the late wet period across the sites (mean difference of 289±53gm^{-2}, $t<0.05$). This is in line with rainfall-biomass production relationships in the rangelands. Coughenour *et al.* (1990) showed that herbaceous production in the rangelands is significantly and positively related to rainfall. Herbaceous production declines across decreasing rainfall gradients, overriding other factors such as soils and topography (Augustine 2003). Furthermore, primary production occurs in pulses, corresponding to rainfall amounts that are rapidly attenuated as the dry season sets in. This also reflects the variable nature of rainfall in the rangelands. Thus, herbaceous vegetation production is episodic and closely linked to rainfall (Ekaya *et al.* 2001). Biomass production increases with increasing rainfall, and usually attains peak values by mid season. As the season progresses, productivity declines and grazing animals begin to deplete the available biomass. In the dry season, plants tend to accumulate more structural compounds, which in turn increase the standing biomass. However, this biomass is largely of limited grazing value because of declining digestibility associated with advancing plant maturity (Baumont *et al.* 2000).

Site A with conservative stocking rates and protected grazing (the ranch) had more abundant perennials than the agropastoral herding zones B and C. The agropastoral grazing areas were subjected to widespread uncontrolled grazing pressure that contributed to low availability of perennial grasses.

A total density of 920, 917 and 755 woody plants ha^{-1} was recorded in sites A, B and C, respectively (Table 4.4). The most abundant woody plants (accounting for over 8% of the relative density) were *Grewia similis* and *Dichrostachyus cinerea* in site A; *Acacia tortilis*, *Premna hildebrandtii*, *Combretum exalatum* and *G. bicolar* in site B; *A. tortilis*, *G. similis*, *G. villosa* and *Boscia coriace* in site C.

Table 4.4. Absolute and relative densities of woody plant species in the study sites

Plant species	Absolute density (plantsha^{-2})			Relative density (%)		
	Site A	Site B	Site C	Site A	Site B	Site C
Cassia cassineria	42	-	-	4.6	-	-
Dichrostachyus cinerea	75	47	-	8.2	5.1	-
Acacia brevispica	30	52	-	3.3	5.7	-
Grewia similis	184	8	67	20.0	0.9	8.9
Acacia tortilis	71	83	219	7.7	9.1	29.0
Tenantia senii	67	36	28	7.3	3.9	3.7
Indigofera lupatana	52	69	-	5.7	7.5	-
Ochna inermis	28	36	1	3.0	3.9	0.1
Steganotaenia araliacea	2	-	-	0.2	-	-
Ormocarpum trachycarpa	18	5	-	2.0	0.5	-
Maerua edulis	42	-	-	4.6	-	-
Maytenus putterlickioides	12	25	-	1.3	2.7	-
Commiphora africana	62	8	38	6.7	0.9	5.0
Jasminum eminii	6	16	-	0.7	1.7	-
Psychotria kirkii	10	8	-	1.1	0.9	-
Premna hildebrandtii	17	76	4	1.8	8.3	0.5
Boscia augustifolia	12	10	-	1.3	1.1	-
Acacia nilotica	19	-	5	2.1	-	0.7
Combretum aculatum	20	83	5	2.2	9.1	0.7
Lannea triphylla	6	-	1	0.7	-	0.1
Grewia villosa	6	-	89	0.7	-	11.8
Acacia melifera	43	18	14	4.7	2.0	1.9
Boscia minimafolia	68	-	29	7.4	-	3.8
Thylachium africana	25	-	-	2.7	-	-
Dalbergia melanoxylon	-	52	-	-	5.7	-
Grewia bicolar	-	88	21	-	9.6	2.8
Albizia antihelmintica	-	7	8	-	0.8	1.1
Croton sylvestris	-	21	-	-	2.3	-
Hosludia opposita	-	41	23	-	4.5	3.0
Ocimum saveolensis	-	11	-	-	1.2	-
Clerondron discolor	-	15	-	-	1.6	-
Lonchor carpus	-	34	-	-	3.7	-
Abrus sericea	-	25	-	-	2.7	-
Boswelia hilderbrandtii	-	25	-	-	2.7	-
Cordia ovalis	-	5	-	-	0.5	-
Acalpha fruiticosa	-	3	10	-	0.3	1.3
Acacia senegal	-	10	56	-	1.1	7.4
Adansonia digitata	-	-	1	-	-	0.1
Boscia coriace	-	-	82	-	-	10.9
Terminalia spinosa	-	-	6	-	-	0.8
Sterculia rhynchocarpa	-	-	5	-	-	0.7
Cadaba farinosa	-	-	2	-	-	0.3
Duosperma kilimandscharica	-	-	38	-	-	5.0
Erythroclamis spectabilis	-	-	2	-	-	0.3
Solanum renchii		-	1	-	-	0.1
Total	**920**	**917**	**755**	**100.0**	**100.0**	**100.0**

4.2. GRAZING PATTERNS AND HABITAT USE

The agropastoral herds in the study area were grazed in different microhabitats. This followed a seasonal pattern of habitat use by the households. The households exploited microhabitats that were designated either as wet or dry season grazing areas. Table 4.5, presents average percent feeding time spent by animals in various microhabitats during the wet and dry seasons.

Table 4.5. Microhabitats and seasonal exploitation/feeding time of agropastoral herds

Microhabitat	Mid wet		Late wet		Mid dry		Late dry	
	No of feeding station	% feeding time	No of feeding station	% feeding time	No of feeding station	% feeding time	No of feeding station	% feeding time
Areas of concentrated drainage	4	22.2	5	26.3	12	60	12	57.1
Foothills/slopes	4	22.2	4	21.1	6	30	7	33.3
Sandy/clay plains	10	55.6	10	52.6	2	10	2	9.5
Total	18	100.0	19	100.0	20	100	21	100.0

In the dry season, areas of concentrated drainage that included river valleys, bottomlands and ephemeral drainage ways absorbed the feeding load, taking 57 to 60% of the feeding time. Foothills/slopes and the open sandy/clay plains followed in that order. Areas of concentrated drainage tend to concentrate moisture and allow for more forage production into the dry season. Thus, these areas are key production sites that are reserved for use in the dry season. The open sandy/clay plains tend to have limited moisture concentration and were mainly exploited in the wet season, accounting for 52.6 to 55.6% of the feeding time. Exploitation of the foothills/slopes was intermediate, but taking more grazing load in the dry season than in the wet season. This resource use strategy ensured that the habitat was exploited in a manner that sustained livestock production throughout the year.

4.3. DIET DIVERSITY AND OVERLAP OF THE HERDS

Seasonal diet diversity by animal species and the aggregate herd are presented in Table 4.6 and Figure 4.1. Patterns of diet diversities were significantly influenced by animal species and season.

Table 4.6. Seasonal diet diversity indices among the three key livestock species

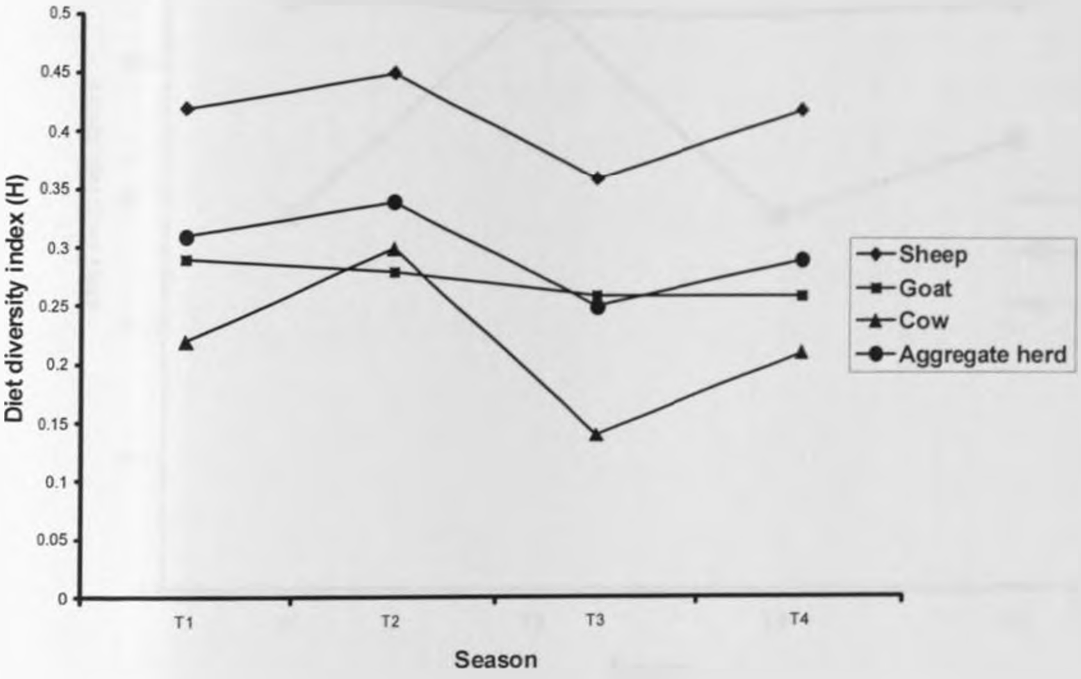
Animal species	Time of grazing			
	MD	LD	MW	LW
Sheep	0.42^{a*}	0.45^{a}	0.36^{a}	0.42^{a}
Goats	0.29^{b}	0.28^{b}	0.26^{b}	0.26^{b}
Cattle	0.22^{c}	0.30^{b}	0.14^{c}	0.29^{b}
Aggregate herd	0.31	0.34	0.25	0.29

*Column means followed by different letter superscripts are significantly different at $p<0.05$
T1 - Mid dry, T2 - late dry, T3 - mid wet, T4 - late wet

All the three animal species (sheep, goats and cattle) exhibited significantly ($p<0.05$) different diets during mid dry and mid wet seasons. Between seasons, sheep and cattle diets varied significantly ($p<0.05$) during the late dry and mid wet season, while goat diets were similar across seasons. The aggregate herd had significantly ($p<0.05$) lower diet diversity in the mid wet season. Sheep and cattle showed a diet diversity trend rising from mid dry to late dry season, then declining to mid wet season before rising to late wet season. In contrast, goats exhibited a slight declining trend in diet diversity from the mid dry to late wet season.

Trends in diet diversity may be attributed to forage biomass availability and selective grazing. The mid and late phases of dry season are usually periods of declining forage availability. This situation forces grazing animals to utilize any available forage to a large extent, resulting in an increase in diet diversity. As forage availability increases during the wet season, animals tend to shift their grazing habits to selective grazing that reduces diet diversity. Diet diversity begins to rise again during the late wet season into the dry period, as forage availability becomes the overriding factor. Goats that are largely selective feeders, generally maintained constant diet diversity across seasons. The observed trends in diet diversity across the animal species were probably reinforced by limited niche space and low plant diversity that are common in agropastoral settings.

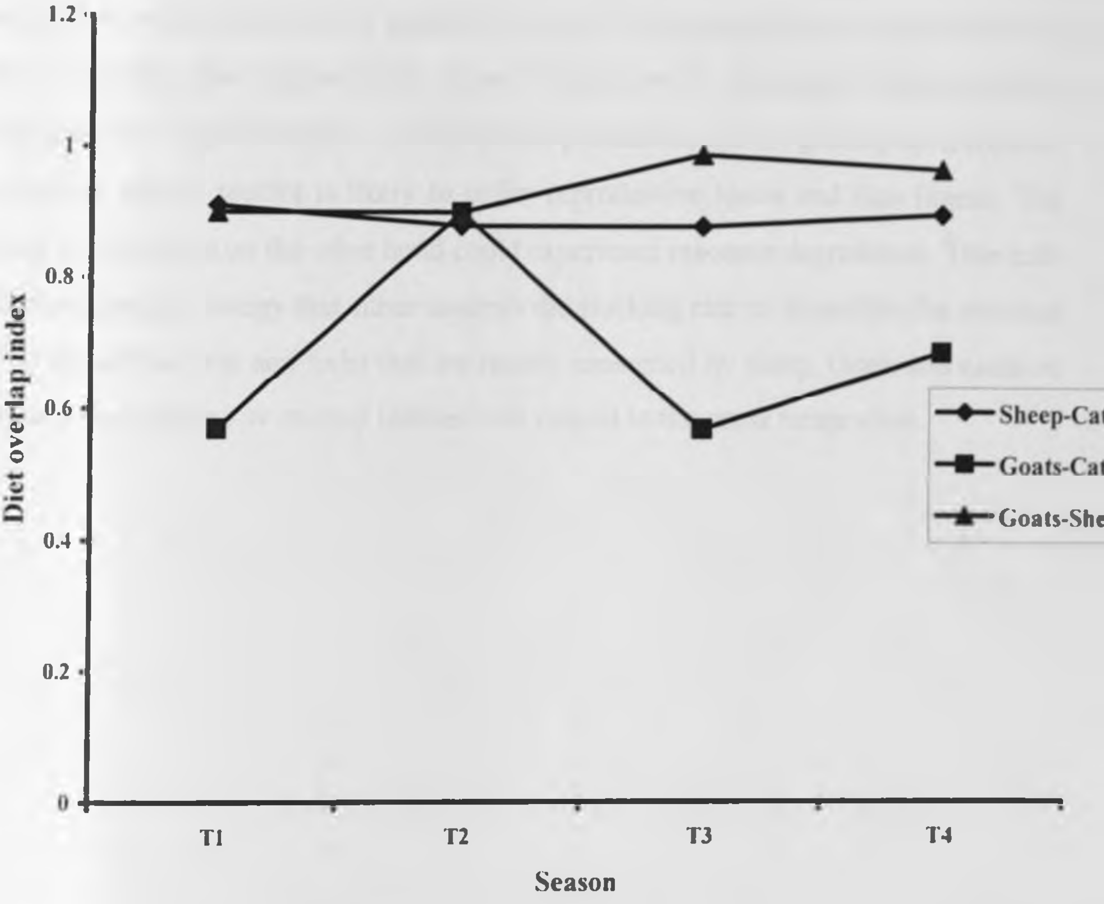
Figure 4.1. Seasonal diet diversity for the animals and aggregate herd



Kilonzo (2003), working in a similar environment, observed sheep diets to be more varied during the dry than the wet season. Otherwise, in areas of a wide niche space and high plant diversity, as in pure pastoral settings, grazing animals tend to have more varied diets during the wet and early dry periods than in mid or late dry periods (Coppock *et al.* 1986).

Seasonal diet overlaps between livestock species are shown in Figure 4.2. Goats and cattle exhibited lower diet similarity than either sheep and cattle or goat and sheep, except during the late dry season.

Figure 4.2. Seasonal diet overlaps among livestock species



Goats are generally mixed feeders that consume large amounts of browse and forbs while cattle are mainly grazers that consume large amounts of grass. Therefore, cattle and goats show relatively low dietary overlap, except in the late dry season (overlap index 0.8) when both species consume large amounts of browse. Both sheep and cattle tend to consume large amounts of grass and forbs and thus exhibit high dietary overlaps across seasons (Figure 4.3 and Figure 4.4). Goats and sheep had high dietary overlaps. Both are mixed feeders (Coppock *et al.* 1986), particularly during the wet seasons over the forbs and browse forage classes (Figure 4.4 and Figure 4.5).

The high dietary overlap index (0.6) with respect to the grass forage between sheep and cattle across seasons, suggests a strong interspecies competition during periods of resource scarcity. Resource scarcity forces animals to aggressively compete for available resources so as to enhance their reproductive fitness. This form of interaction between animal species can have negative effects on both animal production and the grazing environment. The weaker animal species is likely to suffer reproductive losses and thus fitness. The grazing environment on the other hand could experience resource degradation. This calls for a management strategy that either controls the stocking rate or diversifies the resource base to include browse and forbs that are readily consumed by sheep. Goats and cattle or goats and sheep have low overlap indices with respect to the grass forage class.

Figure 4.3. Seasonal dietary overlap between pairs of livestock species for grass across seasons

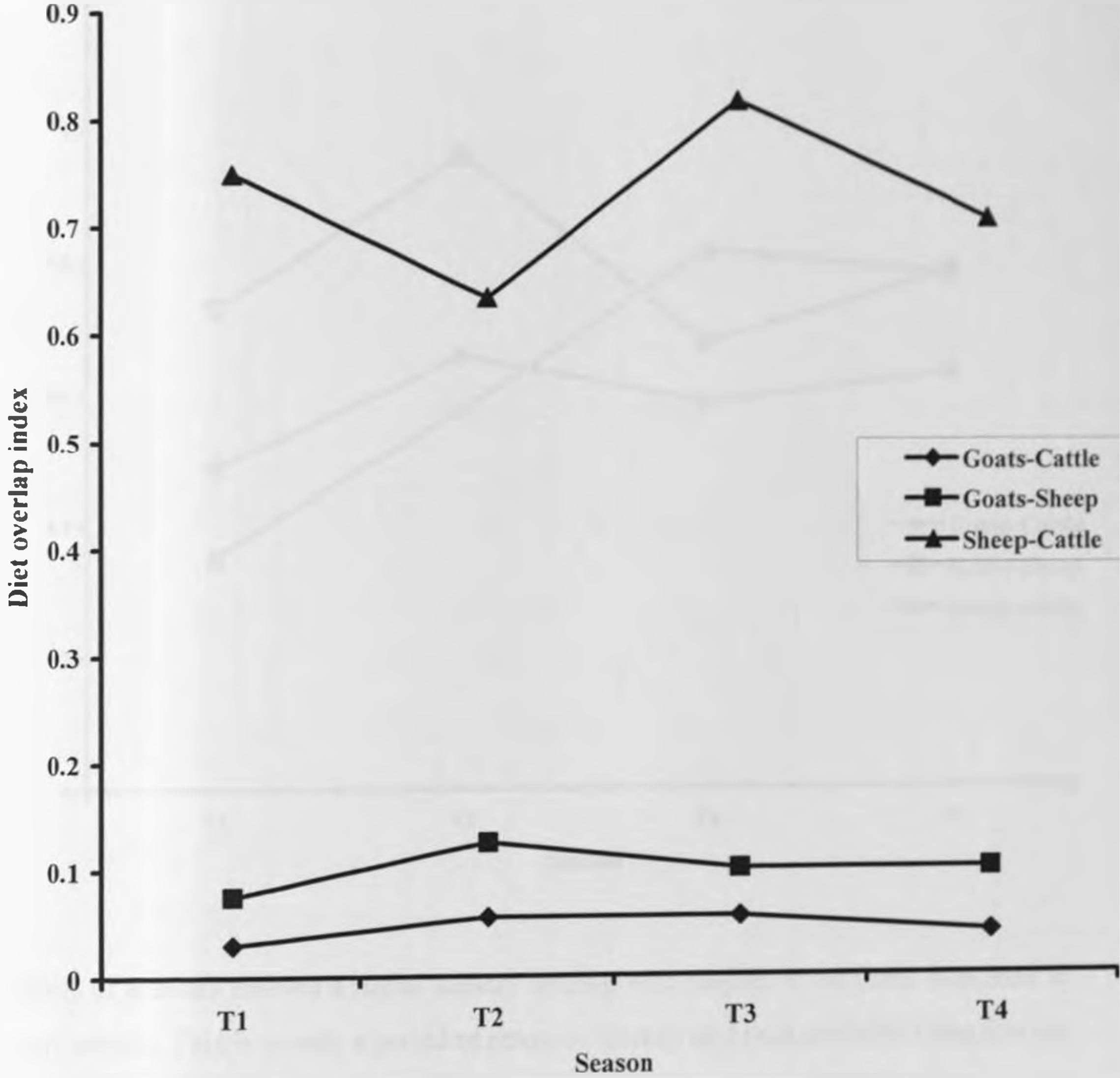
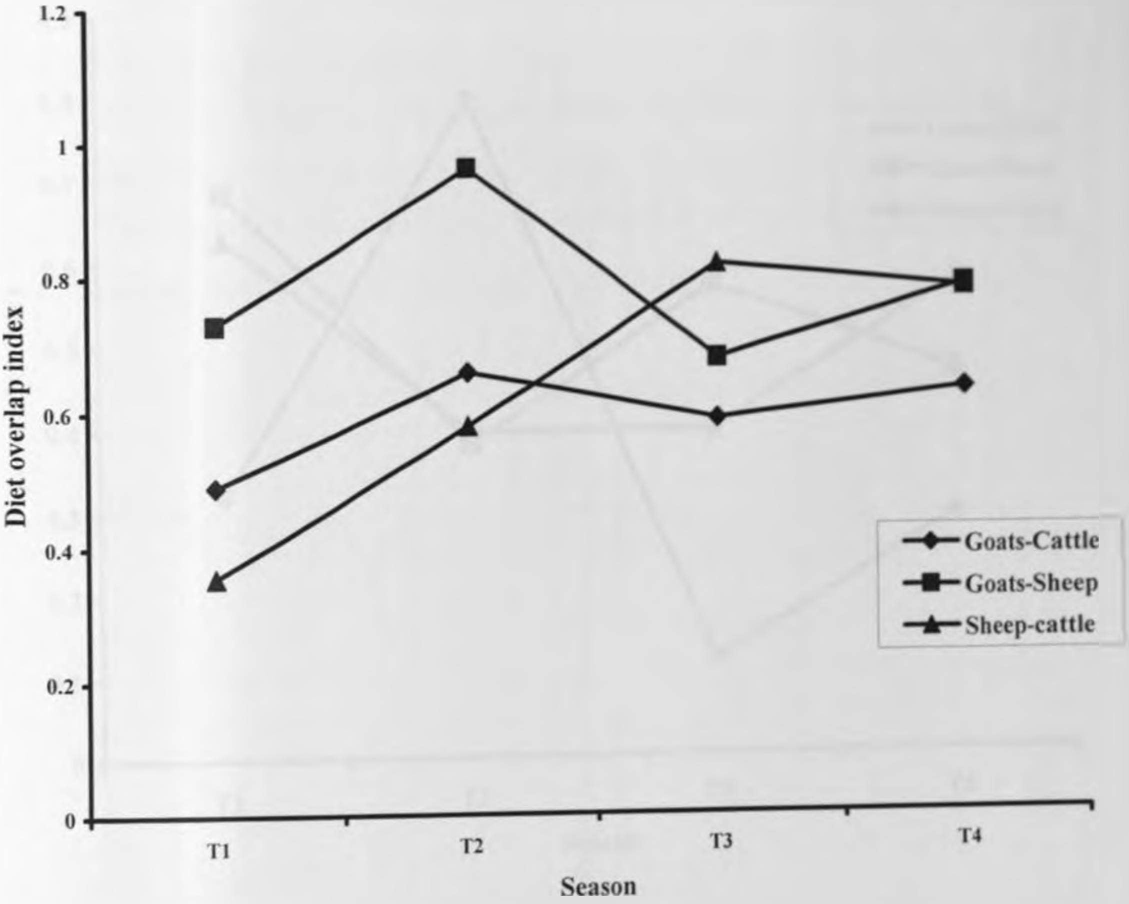
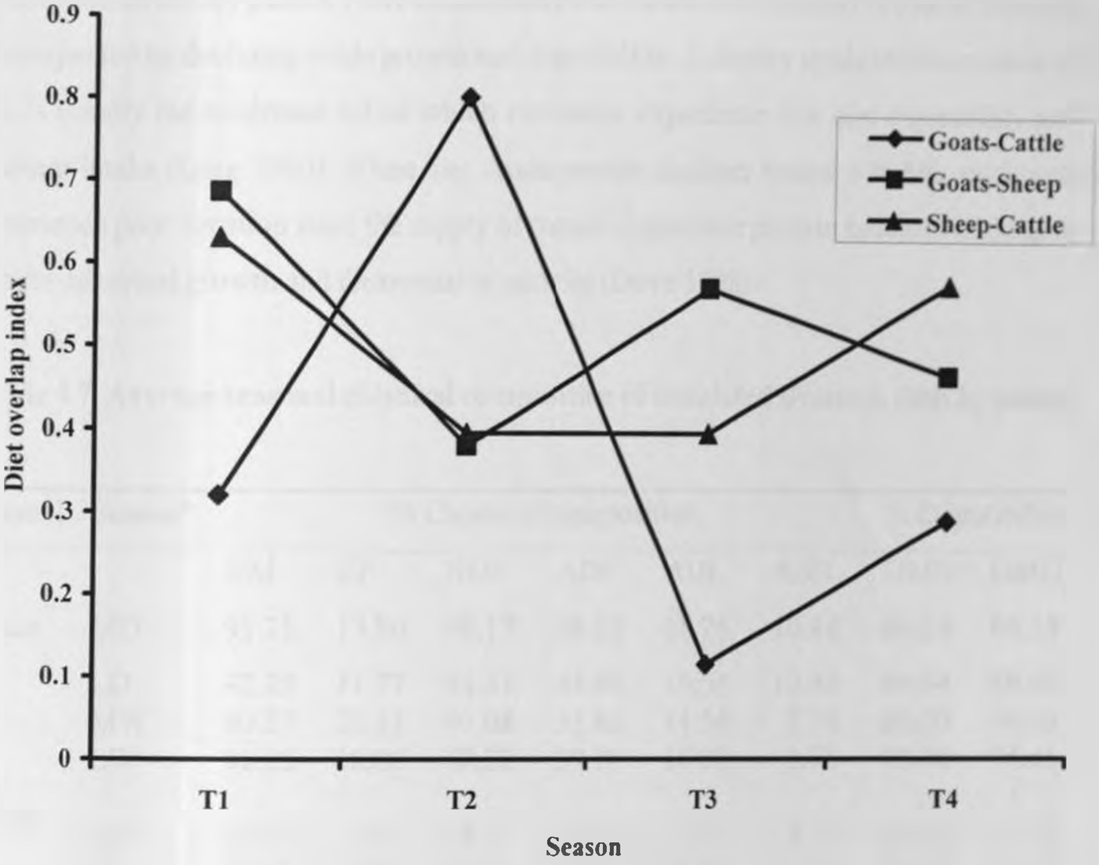


Figure 4.4. Seasonal dietary overlap between pairs of livestock species for forbs across seasons



All pairs of animals showed a higher dietary overlap with respect to the forbs from mid to late dry season. This is usually a period of resource scarcity and thus available forbs that are consumed as supplementary feed by the animals receive greater grazing load.

Figure 4.5. Seasonal dietary overlap between pairs of livestock species for browse across seasons



For all the forage classes, goats and cattle had the lowest seasonal mean diet overlap index (browse = 0.38, grass = 0.045, forbs = 0.59). This suggested that in the study area, in terms of grazing habits, goats and cattle are complementary and not competitive feeders. Sheep and cattle, and sheep and goats had high seasonal mean diet overlap index with respect to grass (0.73) and forbs (0.63), and browse (0.53) and forbs (0.73), respectively. This indicated that during periods of resource scarcity the animals could become competitors.

4.4. SEASONAL CHEMICAL COMPOSITION OF SIMULATED DIETS

Table 4.7, shows the average seasonal chemical composition of the simulated diets of three livestock species. Dietary percent crude protein (CP) and *in vitro* dry matter digestibility

(DMD) or organic matter digestibility (OMD) was higher for all livestock species during the wet season compared to the dry season, whereas percent fibre (NDF and ADF) and lignin were higher in the dry period. Fibre concentration increased with maturity of plants. This was accompanied by declining crude protein and digestibility. A dietary crude protein content of 7% is usually the minimum below which ruminants experience low diet digestibility and nutrient intake (Leng 1980). When diet crude protein declines below 3 to 5%, ruminants experience poor nutrition since the supply of rumen-degradable protein becomes limiting to rumen microbial growth and fermentative activity (Dove 1998).

Table 4.7. Average seasonal chemical composition of simulated livestock diets by season

Animal	Season*	% Chemical composition						% Digestibility	
		DM	CP	NDF	ADF	ADL	ASH	DMD	OMD
Goats	MD	91.21	13.86	48.17	38.82	18.26	10.18	69.14	66.38
	LD	92.25	11.77	55.31	44.98	19.65	12.40	60.94	59.60
	MW	90.27	20.43	40.08	35.86	14.34	7.98	80.50	79.05
	LW	91.22	18.00	47.22	39.21	16.06	9.76	76.96	74.41
Sheep	MD	91.36	9.67	58.41	40.98	9.72	9.32	68.29	67.77
	LD	92.18	8.41	67.67	50.87	12.61	11.34	63.16	62.84
	MW	91.02	15.35	48.93	38.73	7.53	8.03	85.34	84.82
	LW	91.15	11.77	57.43	39.36	8.34	9.11	79.38	78.58
Cattle	MD	92.17	7.58	71.52	50.60	9.54	10.53	62.76	62.32
	LD	92.60	6.34	72.84	52.05	11.73	11.86	58.22	57.64
	MW	91.35	13.55	64.32	42.09	6.80	7.52	84.13	83.34
	LW	91.66	8.98	66.81	45.11	9.17	9.33	76.49	76.06

*Seasons are coded as MD (mid dry), LD (late dry), MW (mid wet) and LW (late wet)

For all seasons, goats harvested diets that were higher in crude protein and low in fibre than sheep and cattle. This showed that goats were more selective closely followed by sheep and then cattle. Thus, based on dietary chemical characteristics, the animals lay in a continuum from concentrate selectors (goats then sheep) to bulk roughage feeders (cattle).

Cattle diets were similar to those of goats for all seasons except mid wet season in terms of *in vitro* organic matter digestibility. However, cattle and sheep diets were significantly different in *in vitro* organic matter digestibility ($p<0.05$) in the dry season, but similar in the wet season (Table 4.8).

Table 4.8. Average seasonal *in vitro* organic matter digestibility of the livestock diets by season

Animal species	Season			
	MD	LD	MW	LW
Goats	66.38^{a}	59.60^{a}	79.05^{ac}	74.41^{a}
Sheep	67.77^{ac}	62.84^{ac}	84.82^{ab}	78.58^{a}
Cattle	62.32^{ab}	57.64^{ab}	83.34^{a}	76.06^{a}

Column means followed by different letter superscripts are significantly different at $p<0.05$

The lack of significant differences in digestibility between goat and cattle diets could be attributed to diet composition. Goats consumed large amounts of non-herbaceous forages that were less digestible, offsetting any advantage conferred by high selectivity to cattle diets that were largely herbaceous. The higher digestibility of sheep diets than cattle diets in the dry season suggested that sheep fed more selectively and had a high crude protein content diet. Increased crude protein content enhance diet digestibility by providing the required nitrogen for rumen microbial fermentation activity. Therefore, in spite of sheep and cattle having similar rumino-reticular volume to body weight ratio (Hanley 1982, Hoffman 1988), diet selection and the attendant chemical composition account for observed differences in digestibility and hence the diet nutritive quality.

4.5. SEASONAL ENERGY INTAKE BY CATTLE, SHEEP AND GOATS

Table 4.9 and Figure 4.6 show seasonal energy intake ($MJday^{-1}$) and trends by the livestock. All the livestock species had a lower and higher energy intake in the dry and wet seasons, respectively. The lowest energy intake was realized in the second late dry season period, a period characterized by very hot and dry conditions. The animals had significantly different energy intakes within and between seasons.

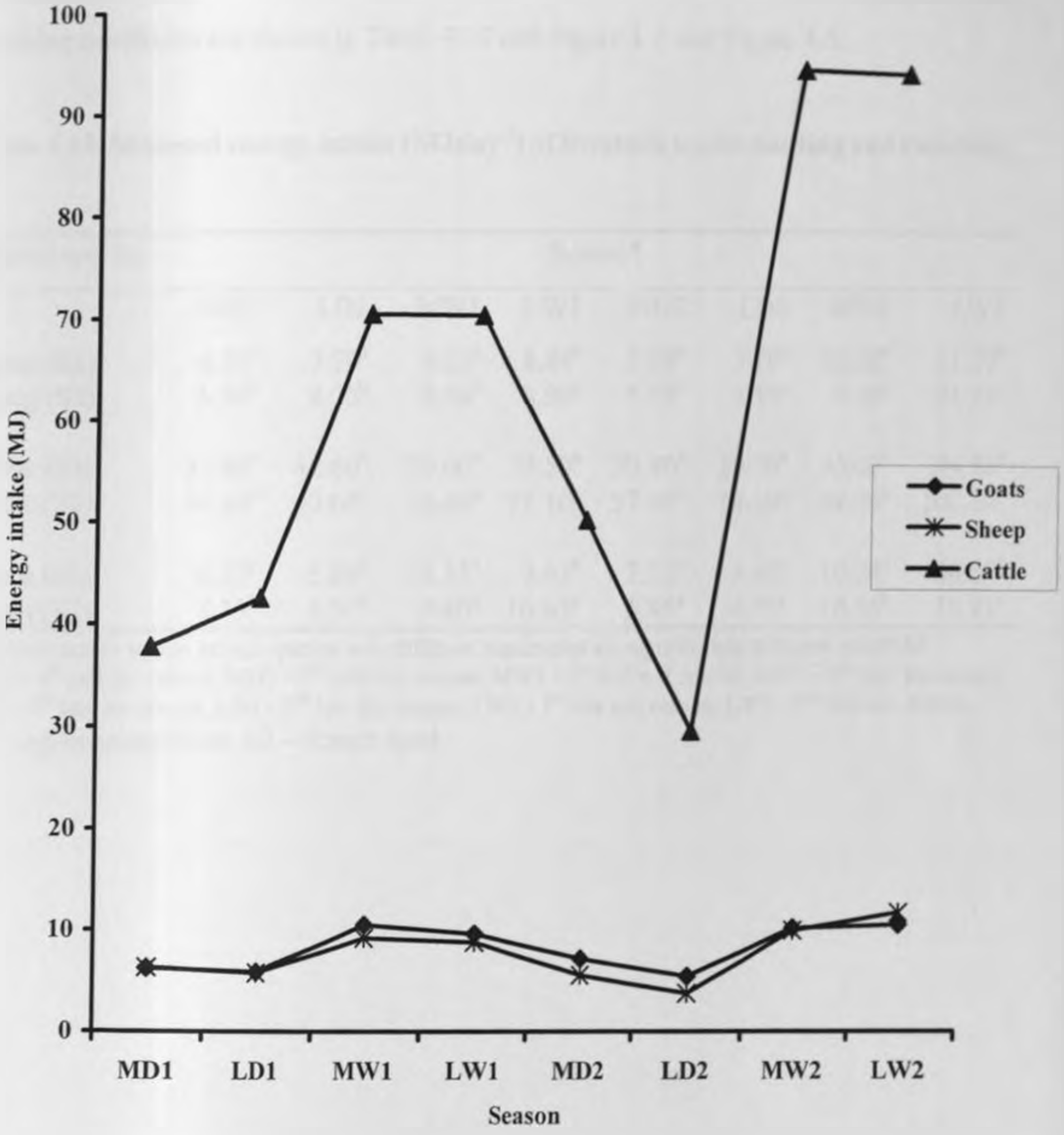
Table 4.9. Seasonal energy intake (MJday^{-1}) by the livestock

Animal species	Season*							
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2
Goats	6.27^{ab}	5.89^{ab}	10.53^{bc}	9.65^{ab}	7.21^{ab}	5.46^{a}	10.24^{bc}	10.57^{bc}
Sheep	6.33^{ab}	5.79^{ab}	9.25^{bc}	8.84^{b}	5.58^{ab}	3.79^{a}	10.02^{bc}	11.77^{c}
Cattle	37.85^{a}	42.60^{a}	70.62^{b}	70.54^{b}	50.39^{b}	29.74^{c}	95.03^{d}	94.76^{d}

Row means followed by different superscripts are significantly different at $p<0.05$

*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MD2 - 2nd mid wet season
LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

Figure 4.6. Seasonal metabolizable energy intake by the livestock



The seasonal (trends in) energy intake profile suggests that animals extract and consume more energy during the wet season when forages are readily digestible than in the dry season when feed digestibility is low. Also, the animals have higher energy intakes overtime, as body size tends to increase with time. Thus, increasing body size dictates a commensurate increase in energy intake to meet increasing metabolic demands.

The seasonal energy intake by the agropastoral livestock compared to those managed under ranching conditions are shown in Table 4.10 and Figure 4.7 and Figure 4.8.

Table 4.10. Seasonal energy intake (MJday^{-1}) of livestock under herding and ranching

Animal species	Season*							
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2
Sheep (S1)	6.33^a	5.79^a	9.25^a	8.84^a	5.58^a	3.79^a	10.02^a	11.77^a
Sheep (S2)	5.50^b	4.70^b	8.56^b	8.99^a	5.75^a	3.59^a	9.30^b	11.21^a
Cattle (S1)	37.80^a	42.60^a	70.60^a	70.50^a	50.40^a	29.70^a	95.00^a	94.80^a
Cattle (S2)	34.40^a	43.60^a	76.60^a	77.10^a	57.40^a	34.30^a	88.00^a	102.30^a
Goats (S1)	6.27^a	5.89^a	10.53^a	9.65^a	7.21^a	5.46^a	10.24^a	10.57^a
Goats (S2)	5.35^a	5.51^a	9.40^a	10.63^a	6.86^a	4.25^a	10.35^a	10.81^a

*Column means within animal species with different superscript are significantly different at $p<0.05$

MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MW2 - 2nd mid wet season

LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

S1 – agropastoral herd, S2 – Ranch herd

Figure 4.7. Seasonal metabolizable energy intake by cattle

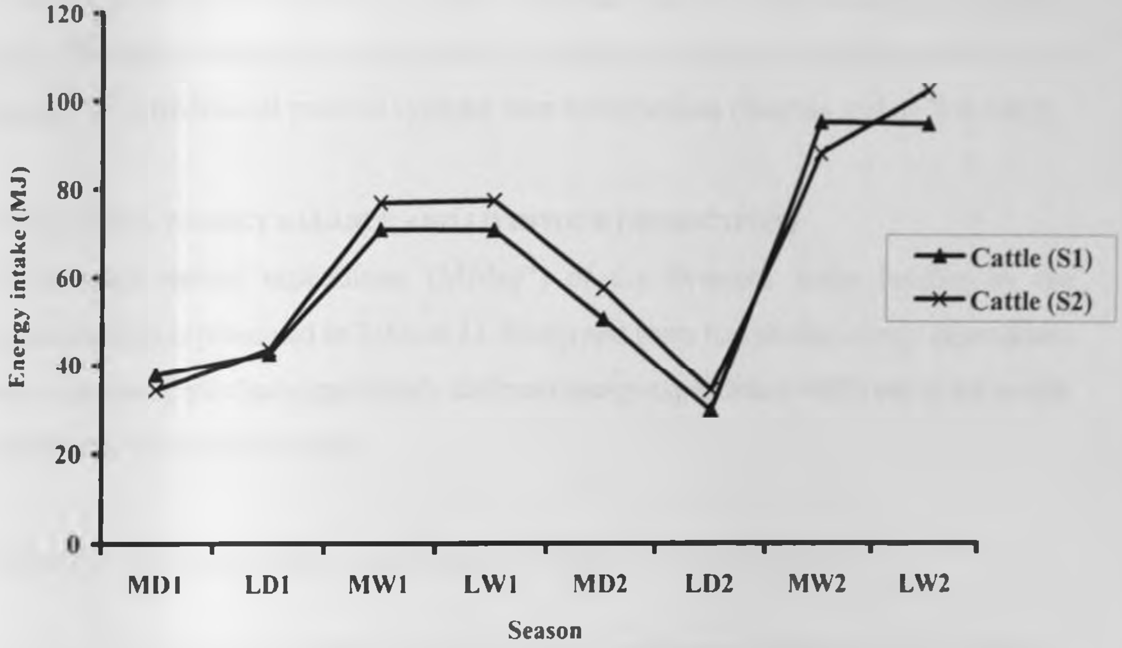
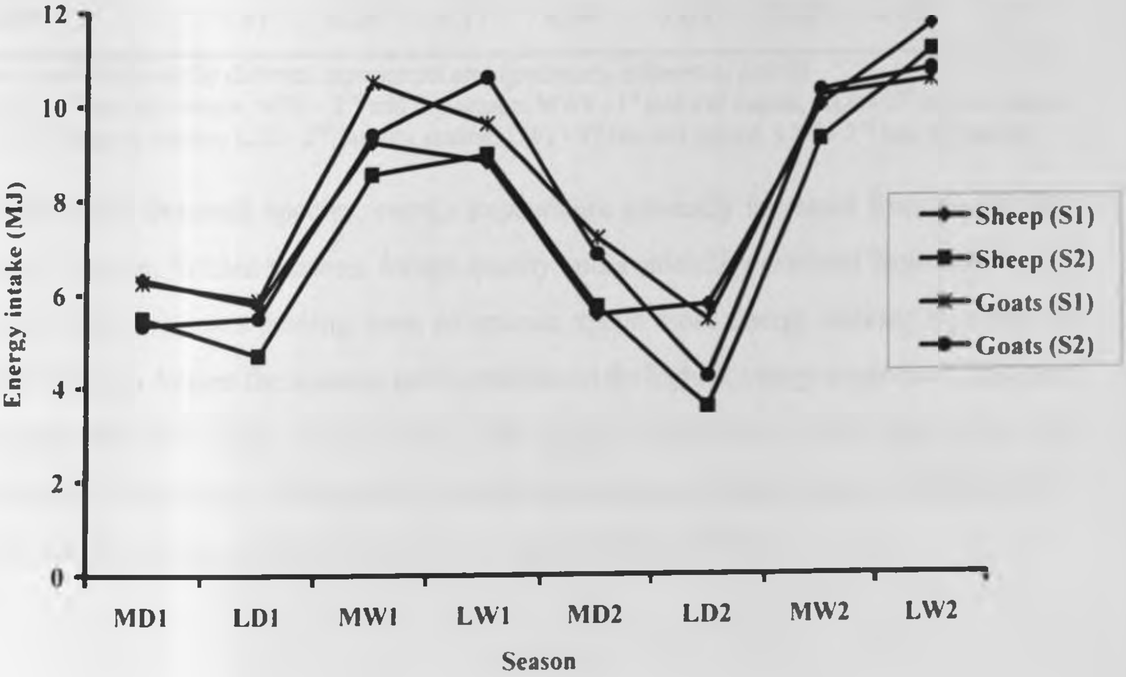


Figure 4.8. Seasonal metabolizable energy intake by sheep and goats



With the exception of cattle, the herded livestock generally had higher energy intake across the seasons. Herding by experienced herdsmen tends to expose animals to micro-sites of high productivity and dietary quality. This allows animals to achieve higher energy and nutrient intake. This phenomenon partly accounts for the observed higher livestock productivity per unit area from traditional pastoral systems than from ranches (Breman and de Wit 1983).

4.6. SEASONAL ENERGY BALANCE AND LIVESTOCK PRODUCTIVITY

The seasonal energy expenditure (MJday^{-1}) of the livestock under herding by the agropastoralists is presented in Table 4.11. Sheep and goats had similar energy expenditure across seasons. Cattle had significantly different energy expenditure within wet or dry season and between wet and dry season.

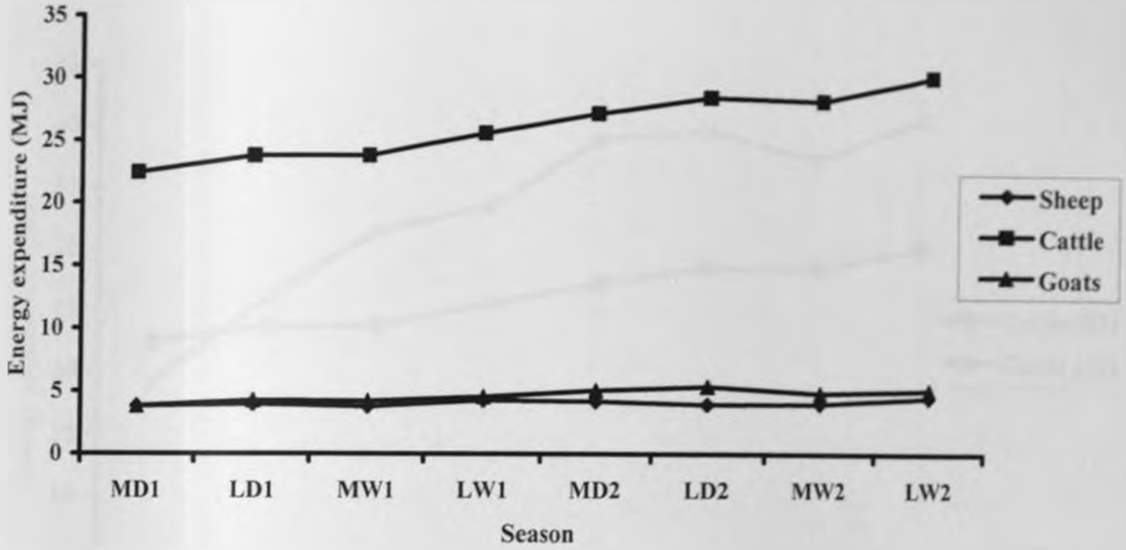
Table 4.11. Seasonal energy expenditure (MJday^{-1}) of the livestock

Animal species	Season*							
	MW1	LW1	MW1	LW1	MD2	LD2	MW2	LW2
Sheep	3.79^{a}	3.96^{a}	3.76^{a}	4.26^{a}	4.18^{a}	3.95^{a}	4.03^{a}	4.54^{a}
Cattle	22.40^{a}	23.67^{a}	23.68^{a}	25.49^{b}	27.07^{bc}	28.38^{c}	28.18^{c}	30.18^{d}
Goats	3.81^{a}	4.24^{a}	4.17^{a}	4.54^{a}	5.04^{a}	5.36^{a}	4.86^{a}	5.12^{a}

Row means followed by different superscripts are significantly different at $p<0.05$
*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MD2 - 2nd mid wet season
LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

For the three livestock species, energy expenditure generally increased from mid to late wet/dry season. Within seasons, forage quality and availability declined from mid to late season. This increases feeding costs as animals spend more energy walking in search of quality forage. Across the seasons, cattle maintained the highest energy expenditure followed by goats and then sheep (Figure 4.9). This is partly attributed to their large body size compared to smallstock. On the other hand, goats maintained higher energy expenditure than sheep across seasons probably due to their high activity patterns.

Figure 4.9. Seasonal energy expenditure of the livestock



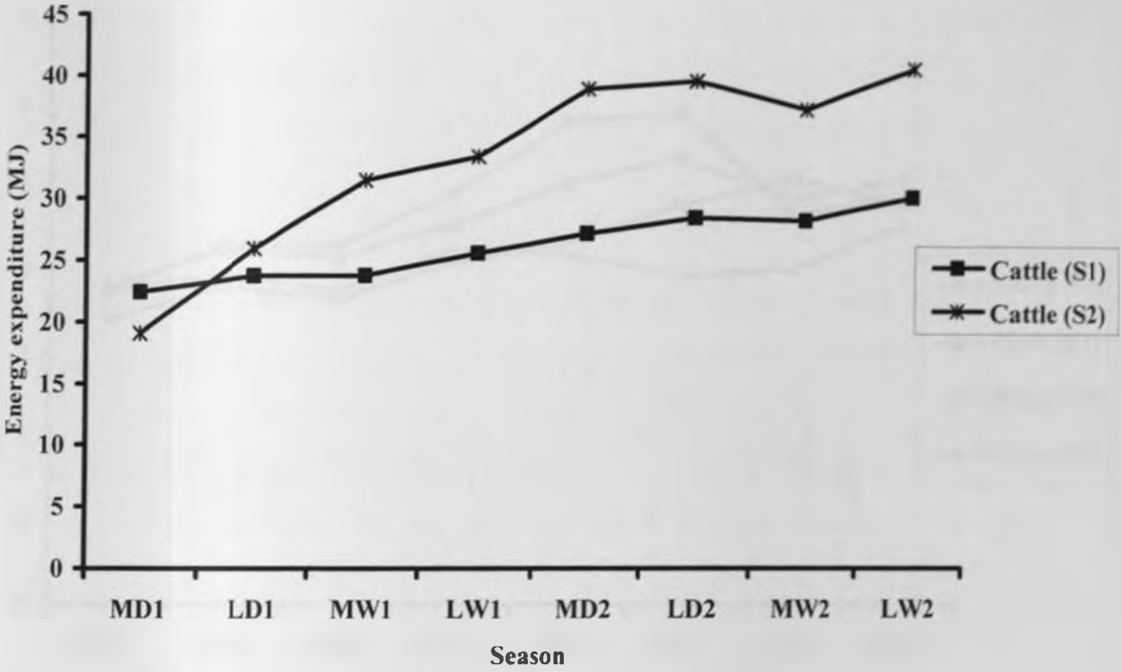
The energy expenditure of the animals under agropastoral herding was generally lower than for the same species, managed along a model ranch (Table 4.12, Figure 4.10 and Figure 4.11) across seasons. Cattle had significant differences in energy expenditure across seasons except in the first late dry season. Sheep and goats had no significant seasonal differences.

Table 4.12. Seasonal energy expenditure of herded and unherded livestock

Animal species	Season*							
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2
Cattle (S1)	22.40^a	23.67^a	23.68^a	25.49^a	27.07^a	28.38^a	28.18^a	30.13^a
Cattle (S2)	19.07^b	25.84^a	31.32^b	33.25^b	38.80^b	39.47^b	37.22^b	40.60^b
Sheep (S1)	3.79^a	3.96^a	3.76^a	4.26^a	4.18^a	3.95^a	4.03^a	4.54^a
Sheep (S2)	3.42^a	3.80^a	3.67^a	4.10^a	4.33^a	4.79^a	5.13^a	4.80^a
Goats (S1)	3.81^a	4.24^a	4.17^a	4.54^a	5.04^a	5.36^a	4.86^a	5.12^a
Goats (S2)	3.77^a	4.31^a	4.29^a	4.93^a	5.78^a	5.87^a	4.66^a	4.94^a

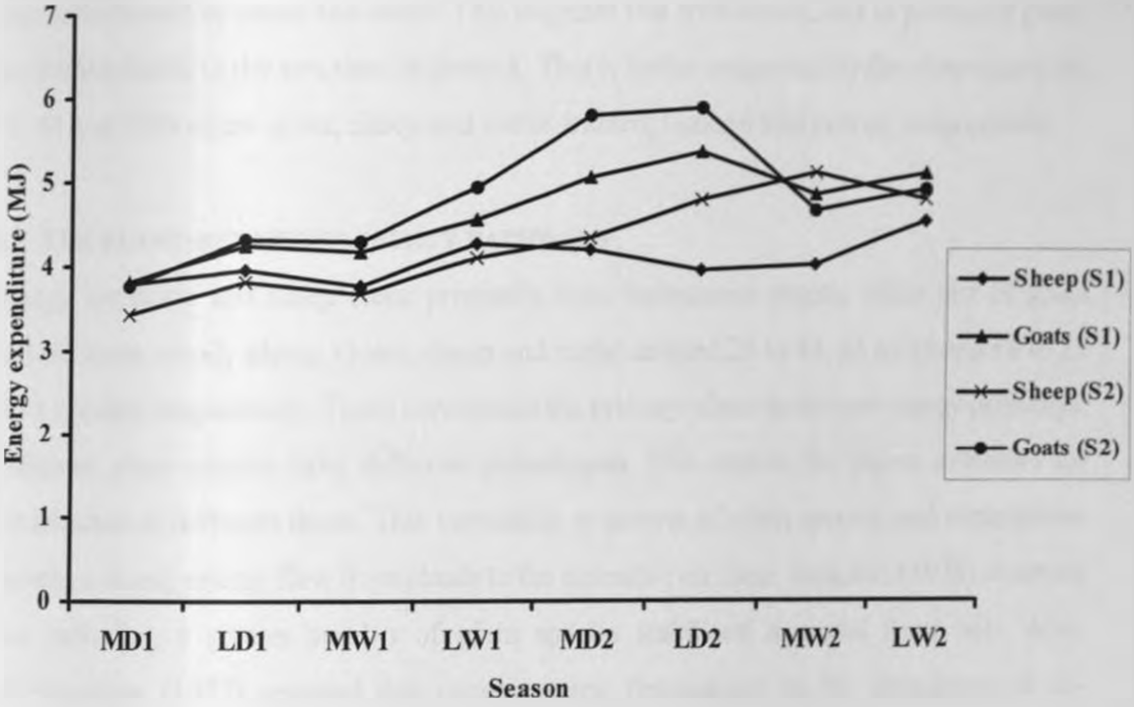
Column means within animal species with different superscript are significantly different at $p<0.05$
*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MD2 - 2nd mid wet season
LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

Figure 4.10. Seasonal energy expenditure of herded and unherded cattle



The significantly ($p<0.05$) higher energy expended by cattle under the ranch model than the agropastoral herds, suggests that the current ranch management practices in the area may not be efficient. The grazing area within the ranch was rarely managed to improve vegetation quality. This may have limited availability of quality grazing and increased feeding costs. The agropastoral herds were usually moved across micro-environments of quality grazing that probably minimized feeding costs and enhanced energy intake. Also, the agropastoral were given crop residues as supplements that enhanced their overall energy intakes. Therefore, it is important for ranchers to institute grazing management practices that enhance the availability of quality grazing. This may partly involve regular burning to remove accumulation of dead plant material and enhance regrowth of high quality, and proper grazing to maintain a vegetation of desirable quality. In the agropastoral areas, grazing the vegetation closely and burning to maintain quality were often practiced.

Figure 4.11. Seasonal energy expenditure of herded and unherded sheep and goats



Animals were in a negative energy balance only in the second late dry season. During this period, 100, 100 and 67% of the cattle, sheep and goats, respectively, in the ranch lost weight and were in a negative energy balance. In contrast, 50, 67 and 33% of the cattle, sheep and goats, respectively, lost weight and were in a negative energy balance in the agropastoral herds. Energy intakes of the animals were determined by bite size and grazing time. For all the livestock species, bite size declined from the wet to dry season. It averaged 0.13 to 0.17, 0.11 to 0.13, and 0.63 to 0.77g for goats, sheep and cattle, respectively, in the dry season. In the wet season, it ranged between 0.2 to 0.22, 0.15 to 0.17, and 0.89 to 0.97g for goats, sheep and cattle, respectively. Grazing time ranged from 4.8 to 5.0 and 5.2 to 5.5 hours in the wet and dry season for the herded animals, respectively. While in the ranch, grazing time ranged between 4.1 to 4.3 and 4.2 to 4.5 hours in the wet and dry season, respectively. The increasing grazing time in the dry season may not have adequately counteracted the declining bite sizes, and hence the animals lost weight.

Based on the energy balance, goats maintained a superior position and, thus, were relatively hardier followed by sheep and cattle. This suggests that smallstock, and in particular goats, are more suitable to the area than largestock. This is further supported by the observation that 78, 44 and 33% of the goats, sheep and cattle, kidded, lambed and calved, respectively.

4.7. THE PLANT-HERBIVORE ENERGY PATHWAYS

Energy for cattle and sheep came primarily from herbaceous plants, while that of goats derived from woody plants. Goats, sheep and cattle utilized 25 to 44, 25 to 35 and 18 to 29 plant species, respectively. These constituted the primary plant-herbivore energy pathways. Different plant species have different phenologies. This makes the plants available for exploitation at different times. This variability in growth of plant species and exploitation ensures a steady energy flow from plants to the animals over time. Saunders (1978) observed that including a greater number of plant species stabilized a model food web. Also, McNaughton (1977) reported that compensating fluctuations in the abundance of co-occurring plant species stabilized total primary production against environmental disturbances. This increased diversity at the primary producer level stabilized energy flow in the aggregate food web or system. Furthermore, keeping different livestock species ensured a broad based forage resource extraction strategy that enhanced energy availability in the form of livestock products for human consumption throughout the seasons.

The plant species that contributed over 50% of the total energy intake by the animals are presented in Tables 4.13, 4.14 and 4.15. For cattle, the most important energy resources were grasses that accounted for over 72% of the total energy intake by the animals (Table 4.13). The single largest energy flow pathway was through *Enteropogon macrostachyus* (33.5%), followed by *Panicum maximum* (9.9%) and *Eragrostis superba* (7.3%).

Table 4.13. Seasonal contribution of important plant species to total energy intake by cattle

Plant species	% seasonal energy contribution*								Average
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2	
Perennial grasses									
Panicum maximum	17.6	7.5	14.0	11.5	7.2	-	11.7	9.5	9.9
Eragrostis superba	9.1	2.7	9.8	4.8	8.4	5.4	7.3	10.6	7.3
Enteropogon macrostachyus	13.9	42.5	34.6	37.2	37.9	31.2	39.0	31.4	33.5
Digitaria milanjiana	-	-	11.1	10.9	2.8	-	2.9	8.8	4.6
Chloris roxyburghiana	-	-	-	4.2	-	2.3	-	-	0.8
Eragrostis caespitosa	-	-	-	-	0.9	-	-	-	0.1
Annuals	35.6	11.4	18.8	7.8	7.4	-	22.7	21.5	15.7
Achyranthes aspera	3.4	-	-	-	-	-	-	-	0.4
Sida ovata	-	-	3.6	-	-	-	-	-	0.5
Blepharis integrifolia	-	-	-	3.7	-	0.3	-	-	0.5
Vigna ungunculata	-	-	-	-	-	3.9	-	-	0.5
Other forbs	-	-	-	-	-	-	10.0	0.6	2.3
Zea mays stover	-	10.6	-	-	-	22.7	-	-	4.2
Barleria taitensis	-	-	-	-	16.5	-	-	-	2.1
Combretum exalatum	-	2.1	-	-	-	-	-	-	0.3
Cajanus cajan	-	-	-	-	-	6.0	-	-	0.8
Acacia tortilis pods	-	-	-	-	-	16.5	-	-	2.1

*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MW2 - 2nd mid wet season LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

The large overall energy contribution by grasses confirms that cattle are grazers. The perennials played a major role in meeting the animals' energy requirements. Annuals were also important. Therefore, to meet energy requirements of cattle in this system, the production and management of perennial grasses is critical. Annuals should also be managed as a complementary annual crop. Crop residues could be kept for critical periods like the harsh second dry period.

Sheep extracted a large proportion of their energy from grasses, followed by forbs and browse (Table 4.14). Perennial grasses accounted for over 30.7% of the energy intake by sheep, with *Enteropogon macrostachyus* being the main energy pathway. The annuals accounted for 15%, making the grasses to contribute about 45.7% of the total energy intake.

Table 4.14. Seasonal contribution of important plant species to total energy intake by sheep

Plant species	% seasonal energy contribution*								Average
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2	
Perennial grasses									
Panicum maximum	-	-	7.5	6.2	9.2	-	2.7	6.5	5.3
Eragrostis superba	7.0	5.5	7.1	5.9	8.3	-	-	9.7	5.4
Enteropogon macrostachyus	8.6	15.4	29.6	7.7	13.6	19.0	29.8	8.9	16.6
Digitaria milanjian	-	-	4.8	16.0	6.3	-	-	0.4	3.4
Annuals	27.5	18.1	16.5	-	4.2	-	26.2	27.5	15.0
Blephalis integrifolia	6.0	18.0	-	10.9	35.9	11.2	-	-	10.3
Teprosia villosa	12.6	10.9	-	9.6	-	-	7.8	9.3	6.3
Pavonia patens	-	4.9	-	-	-	-	-	-	0.6
Astripomea hyocyamoides	-	-	-	3.6	-	-	-	-	0.5
Other forbs	2.8	-	-	-	-	8.5	12.9	9.8	5.5
Barleria taitensis	-	-	-	-	6.2	-	-	-	0.8
Premna hilderbrandti	-	-	-	-	-	-	6.0	-	0.8
Grewia similis	-	-	7.1	-	-	-	-	-	0.9
Duosperma kilimandscharica	-	-	3.6	-	-	4.0	5.3	3.8	2.1
Cajanus cajan		-	-	-	-	23.9	-	-	3.0
Acacia tortilis pods	-	-	-	-	-	7.6	-	-	1.0

*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MW2 - 2nd mid wet season LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

Important forbs and browse accounted for 23.2 and 8.6% of the energy intake, respectively. *Blepharis integrifolia* was the main forb that contributed 10.3% of the energy intake by the sheep. Sheep were largely mixed feeders, requiring all of the forage classes to satisfy their energy demands.

Browse and forbs accounted for over 73.2% of the energy intake by goats (Table 4.15). *Duosperma kilimandscharica* and *Combretrum exlatum* were the main browse species contributing 11.7 and 10.7%, respectively, of the energy intake by the goats. *Tephrosia villosa* and *Blepharis integrifolia* were the main forbs. The goats were largely browsers, given the high contribution of browse to the overall energy intake by them.

Table 4.15. Seasonal contribution of important plant species to total energy intake by goats

Plant species	% seasonal energy contribution*								Average
	MD1	LD1	MW1	LW1	MD2	LD2	MW2	LW2	
Grewia similis	14.0	7.6	20.3	15.5	-	-	7.2	6.2	8.9
Dichrostachyus.cinerea	6.2	5.3	5.0	5.0	3.8	-	1.1	1.9	3.5
Duosperma kilimandscharica	5.4	10.3	10.7	-	10.4	26.0	17.2	13.9	11.7
Combretum exalatum	6.5	18.5	12.7	6.5	18.2	-	10.7	11.8	10.7
Barleria taitensis	4.8	-	-	-	10.2	-	-	-	1.2
Ochna inermis	-	23.5	-	-	-	-	-	4.8	3.5
Grewia villosa	-	5.3	-	-	-	-	-	-	0.7
G. bicolor	-	-	12.5	-	-	-	-	-	1.6
Hosludia opposita	-	-	5.0	-	-	-	8.0	4.7	2.2
Prema hilderbrandtii	-	-	10.8	19.6	-	-	4.8	4.3	4.9
Tenantia senii	-	-	-	11.3	-	-	-	-	1.4
Cajanus cajan	-	-	-	-	-	9.1	-	-	1.1
Acacia tortilis	19.4	-	-	-	-	-	4.2	-	3.0
A. tortilis pods	-	-	-	-	-	27.8	-	-	3.5
A. mellifera pods	-	-	-	-	-	0.9	-	-	0.1
Omocarpum trachycarpa	-	-	-	-	-	-	-	2.9	0.4
Commiphora Africana	-	-	-	-	-	-	-	14.5	1.8
Tephrosia villosa	7.1	8.7	-	10.8	-	-	11.9	7.7	5.8
Monechma debile	9.4	-	-	-	5.0	-	-	-	1.8
Blepharis integrifolia	-	-	-	-	23.0	7.9	-	-	3.9
Vigna unguculata	-	-	-	-	-	12.0	-	-	1.5

*MD1 - 1st mid dry season, MD2 - 2nd mid dry season, MW1 - 1st mid wet season, MW2 - 2nd mid wet season
LD1 - 1st late dry season, LD2 - 2nd late dry season, LW1 - 1st late wet season, LW2 - 2nd late wet season

The primary energy pathways (plant-herbivore pathways) in the agropastoral system reflect two complementary modes of resource extraction: woody plant-browsers (goats) energy pathway and perennial grass-grazers (cattle) pathway. Sheep may play an intermediate or competitive role depending on resource availability. When resources are scarce as in the dry period, sheep may become competitive feeders with either goats or cattle. As a basis of stabilizing the energy supply to animals, feed resource management strategies should be centred on the main energy pathways for the specific livestock species.

4.8. ENERGY INTAKE CONSTRAINT CURVES FOR GRAZING CATTLE

Metabolizable energy (ME) intake constraint curves for grazing cattle for four perennial grasses are shown in Figures 4.12, 4.13, 4.14 and 4.15. Based on these curves, energy intake by cattle was optimized at 460, 420, 470 and 480 gm^{-2} of sward biomass, with corresponding grass organic matter digestibility percentages of 60.6, 64.3, 62 and 55.5 for *Enteropogon macrostachyus*, *Panicum maximum*, *Eragrostis superba* and *Chloris roxyburghiana*, respectively. Optimal sward biomass among the grasses varied by a maximum of 60gm. *Chloris roxyburghiana* yielded the highest optimal sward biomass at the lowest digestibility compared to the other grasses. *Panicum maximum* gave the lowest optimal sward biomass that was accompanied by the highest digestibility.

The constraint curves provide a means of optimization of the energy intake by grazing herbivores given the natural variation in forage quality and abundance over space and time. Grazing herbivores are faced with two constraints related to foraging: a cropping constraint and a digestive constraint. Cropping designates the amount of dry matter ingested per bite and is determined by forage availability. Cropping rates and thus energy intake generally increase with plant biomass until a point at which the amount that can be cropped is limited by the animal's mouth dimensions. Thus, the amount cropped increases asymptotically with increasing plant biomass. On the other hand, the digestive constraint sets in with plant maturity. As plants mature, they accumulate structural carbohydrates and decline in nutritive quality as reflected in decreasing digestibility. A cropping curve, therefore, shows the maximum amount of energy an individual animal can consume in the absence of the digestive constraint. In contrast, a digestion curve shows the maximum amount of energy an individual animal can process in the absence of the cropping constraint. Thus, realized energy intake as a function of biomass tracks the minimum of the two constraint curves (Shipley *et al.* 1999, Wilmshurst *et al.* 1999, 2000). The point of intersection of the two curves identifies the maximum energy intake and the optimal sward biomass.

Figure 4.12. Daily ME intake and OMD constraint curves for cattle grazing *Enteropogon macrostachyus*

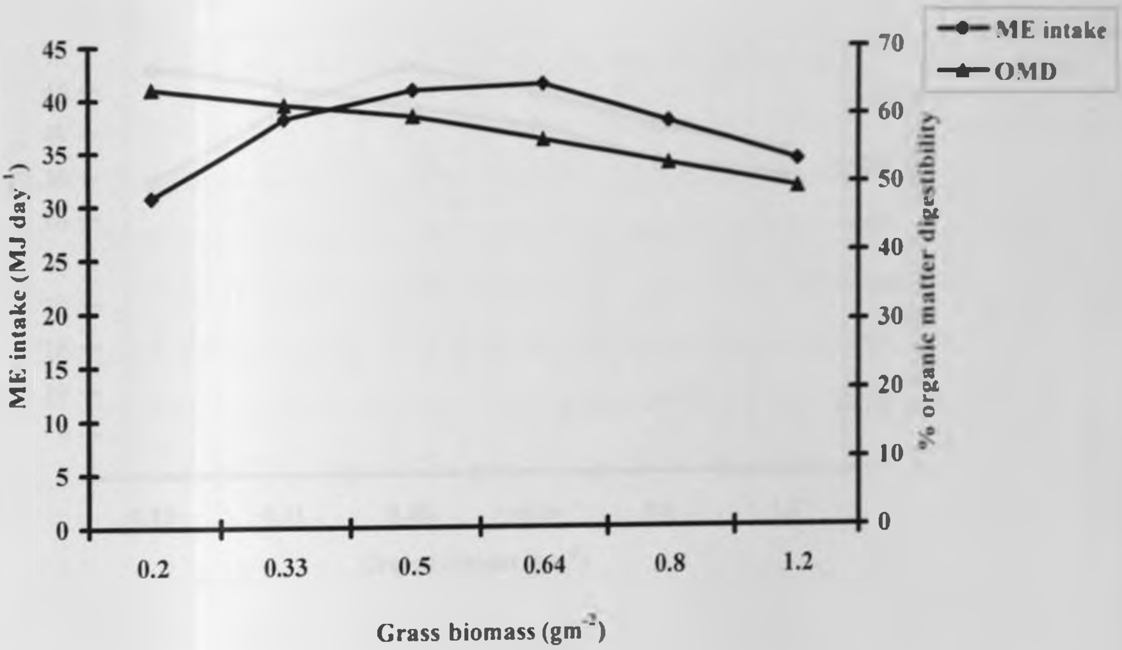


Figure 4.13. Daily ME intake and OMD constraint curves for cattle grazing *Panicum maximum*

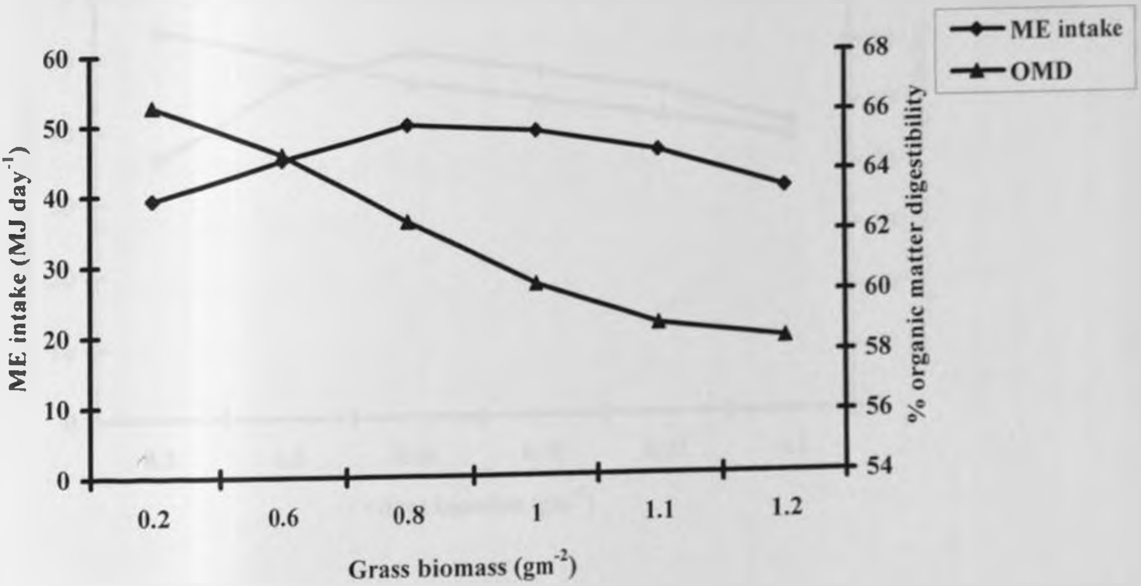


Figure 4.14. Daily ME intake and OMD constraint curves for cattle grazing *Eragrostis superba*

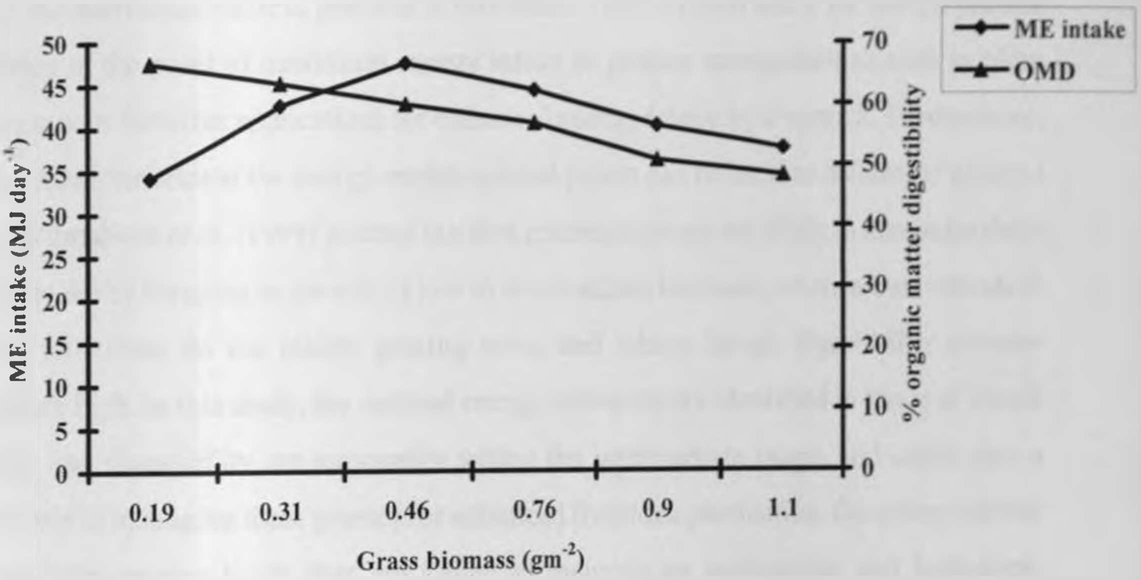
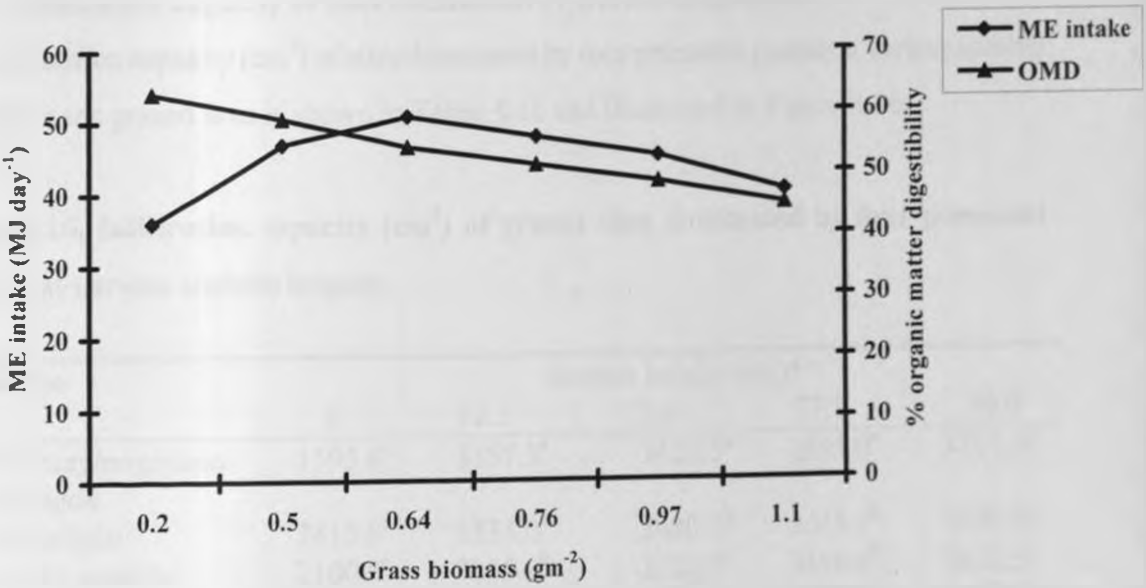


Figure 4.15. Daily ME intake and OMD constraint curves for cattle grazing *Chloris roxyburghiana*



The identification of the maximum energy intake of swards could have important implications for management for increased livestock productivity. For example, using the curves, the nutritional value of pastures is estimated. This can then allow for intense pasture utilization at the point of maximum energy intake or pasture manipulations such as plant species mix or fertilizer applications for enhanced energy intake by livestock. Furthermore, pasture characteristics at the energy intake optimal points can be used to determine when to graze. Wilmshurst *et al.* (1999) pointed out that grazing animals are likely to maximize daily energy intake by foraging on swards of low to intermediate biomass, where either very short or very tall tillers do not inhibit grazing rates, and where forage digestibility remains acceptably high. In this study, the optimal energy intake points identified in terms of sward biomass and digestibility are reasonably within the intermediate range, and could play a central role in managing these grasses for enhanced livestock production. Coupling optimal grazing with grazing levels that are aimed at maintaining appropriate soil hydrologic responses could further enhance livestock production.

4.9. HYDROLOGICAL RESPONSES AND SEDIMENT PRODUCTION OF SITES DOMINATED BY PERENNIAL GRASSES

4.9.1. Infiltration capacity of sites dominated by perennial grasses

The infiltration capacity (cm^3) of sites dominated by four perennial grasses at various stubble heights in the grazed area is shown in Table 4.16 and illustrated in Figure 4.16.

Table 4.16. Infiltration capacity (cm^3) of grazed sites dominated by four perennial grasses at various stubble heights

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	1595.0^{a}	3357.5^{a}	3427.5^{a}	3595.0^{a}	3715.0^{a}
Enteropogon macrostachyus	2415.0^{b}	3335.0^{a}	3480.0^{b}	3645.0^{b}	3690.0^{a}
Eragrostis superba	2100.0^{c}	3065.0^{b}	3220.0^{c}	3450.0^{b}	3632.5^{b}
Panicum maximum	2190.0^{d}	3415.0^{c}	3595.0^{d}	3700.0^{c}	3700.0^{a}

*Column means with different superscript are significantly different at $p<0.05$

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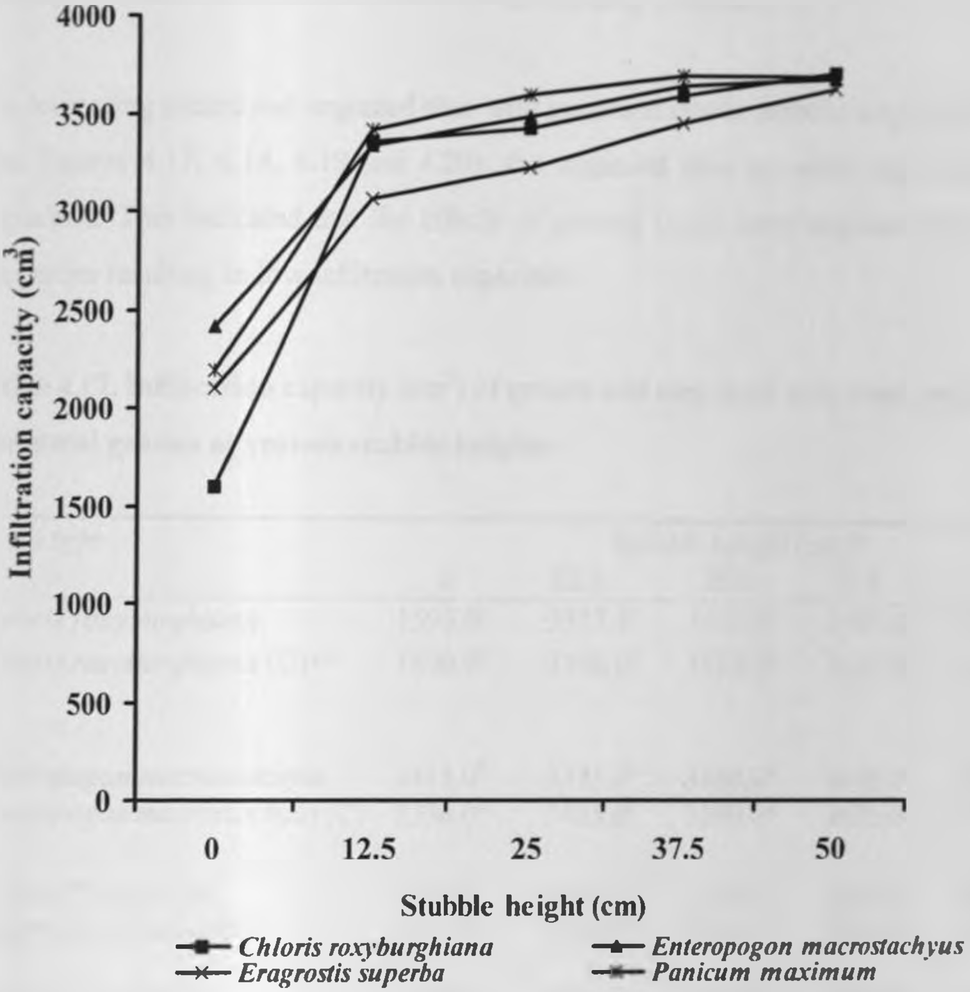
Enteropogon macrostachyus	2415.0^b	3335.0^a	3480.0^b	3645.0^b	3690.0^a
Eragrostis superba	2100.0^c	3065.0^b	3220.0^c	3450.0^b	3632.5^b
Panicum maximum	2190.0^d	3415.0^c	3595.0^d	3700.0^c	3700.0^a

*Column means with different superscript are significantly different at $p<0.05$

Figure. 4.16. Infitration capacity curves of grazed sites dominated by perennial grasses at different stubble heights



Infiltration capacity of sites dominated by the grasses increased with increasing stubble height before levelling off towards the highest stubble height. *Panicum maxmum* site maintained a significantly ($p<0.05$) higher infiltration capacity between 12.5 to 37.5cm stubble height, followed by *Enteropogon macrostachyus*, *Chloris roxyburghiana* and lastly *Eragrostis superba*. This could be attributed to the growth characteristics of the grasses. *Panicum maximum* is leafy and less stemmy. Also, this grass is broad leafed, and thus presents a greater surface area for collecting rainwater that is concentrated more into its rhizosphere. In contrast, *Chloris roxyburghiana and Eragrostis superba* are stemmier and thus less effective in concentrating rainwater into their rhizosphere. *Enteropogon macrostchyus*, though narrow leafed, tends to be more leafy than stemmy and is therefore closely compares with *Panicum maximum* in trapping rainwater.

On comparing grazed and ungrazed sites with grasses at similar stubble heights (Table 4.17 and Figures 4.17, 4.18, 4.19 and 4.20), the ungrazed sites recorded higher infiltration capacities. This indicated that the effects of grazing might have degraded soil physical properties resulting in low infiltration capacities.

Table 4.17. Infiltration capacity (cm^3) of grazed and ungrazed sites dominated by four perennial grasses at various stubble heights

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	1595.0^a	3357.5^a	3427.5^a	3595.0^a	3715.0^a
Chloris roxyburghiana (C)**	1890.0^b	3390.0^b	3515.0^b	3610.0^a	3720.0^a
Enteropogon macrostachyus	2415.0^b	3335.0^a	3480.0^a	3645.0^a	3690.0^a
Enteropogon macrostachyus (C)	2350.0^a	3425.0^b	3590.0^b	3655.0^a	3700.0^a
Eragrostis superba	2100.0^a	3065.0^a	3220.0^a	3450.0^a	3632.5^a
Eragrostis superba (C)	2175.0^b	3130.0^b	3375.0^b	3595.0^b	3605.0^a
Panicum maximum	2190.0^b	3415.0^a	3595.0^a	3700.0^a	3700.0^a
Panicum maximum (C)	1925.0^a	3455.0^b	3640.0^b	3707.5^a	3710.0^a

*Column means within plant species with different superscript are significantly different at $p<0.05$

**C is the control in ungrazed area

Figure 4.17. Infiltration capacity curves for *Chloris roxyburghiana* sites when grazed (GA) and ungrazed (UGA)

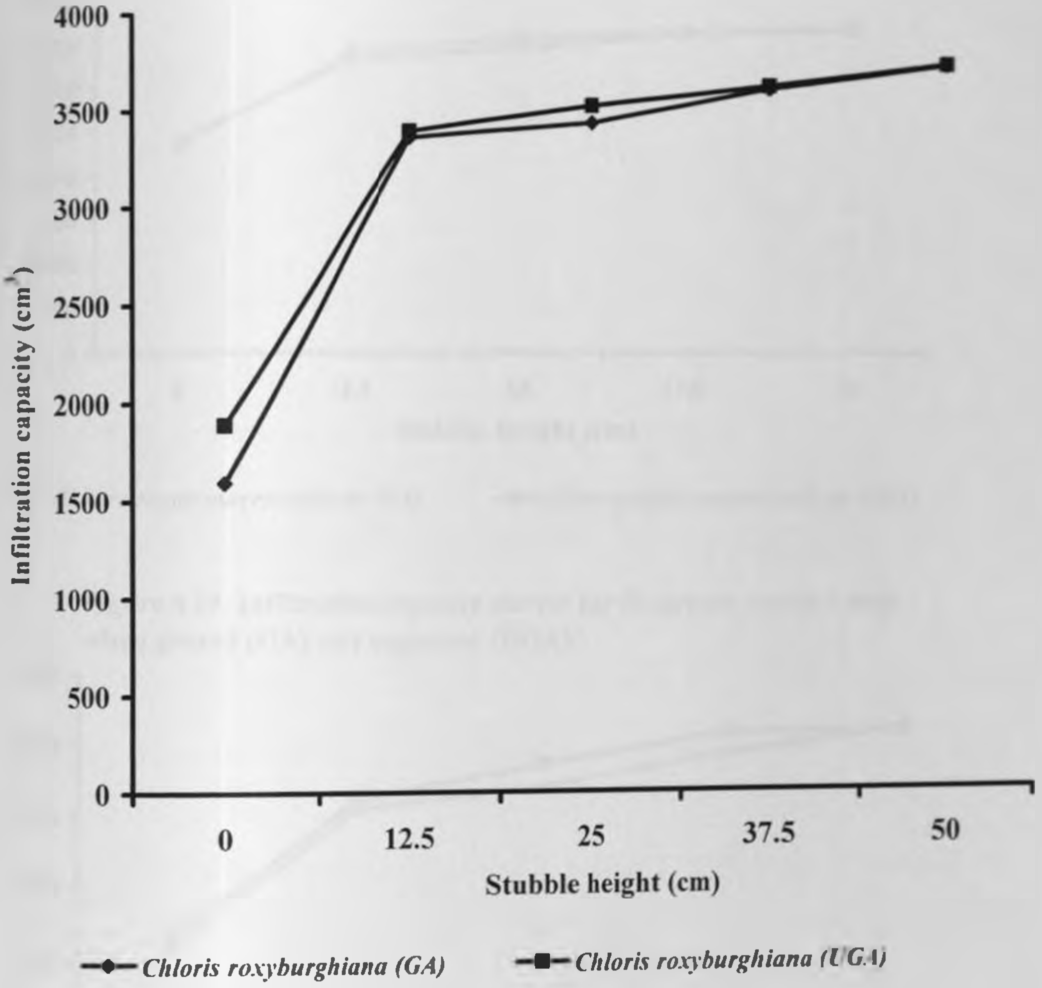


Figure 4.18. Infiltration capacity curves for *Enteropogon macrostachyus* sites when grazed (GA) and ungrazed (UGA)

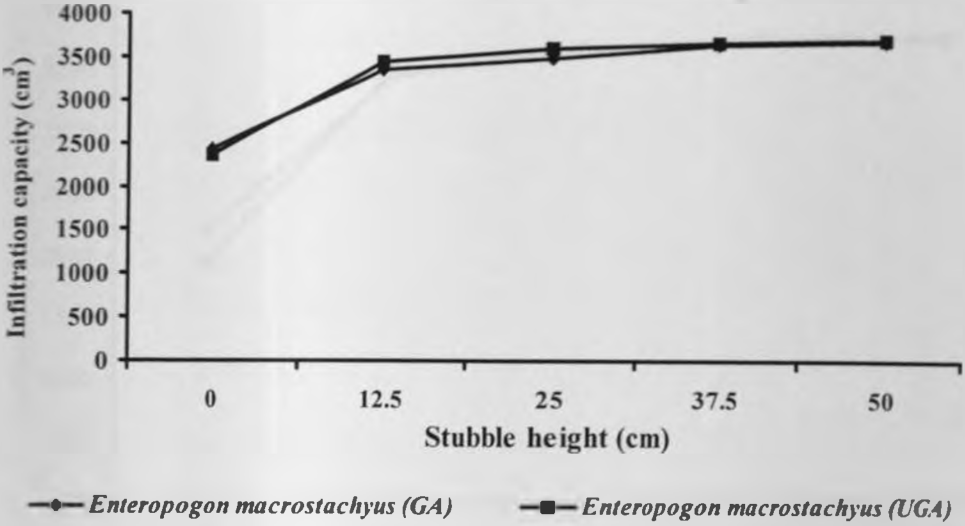


Figure 4.19. Infiltration capacity curves for *Eragrostis superba* sites when grazed (GA) and ungrazed (UGA)

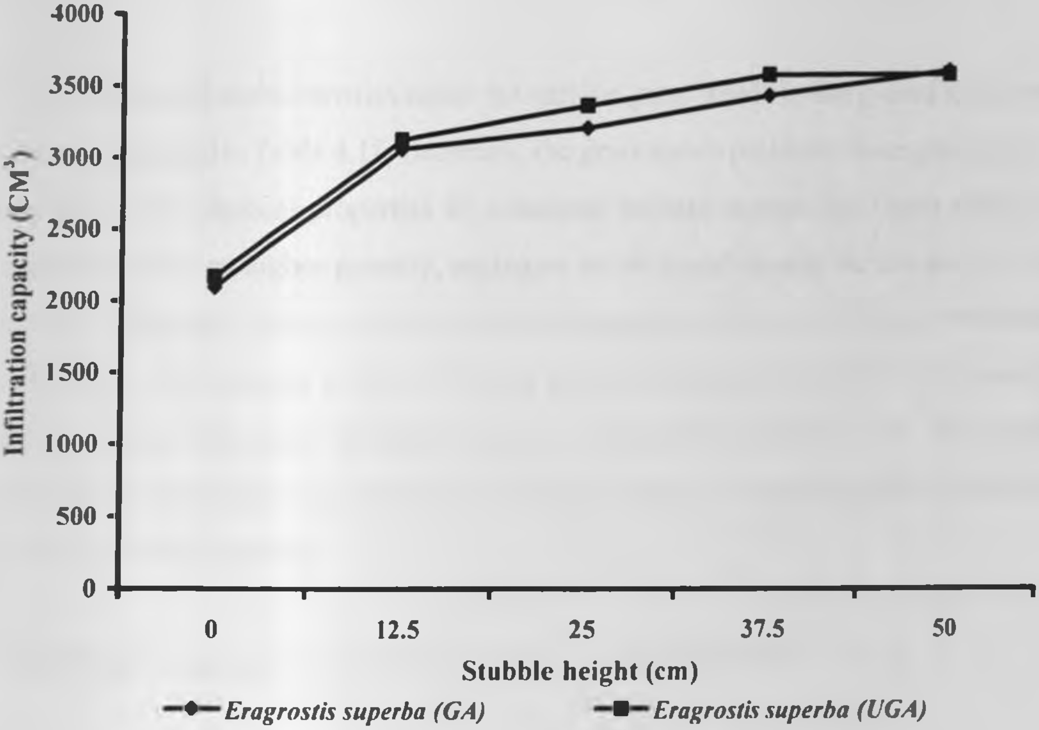
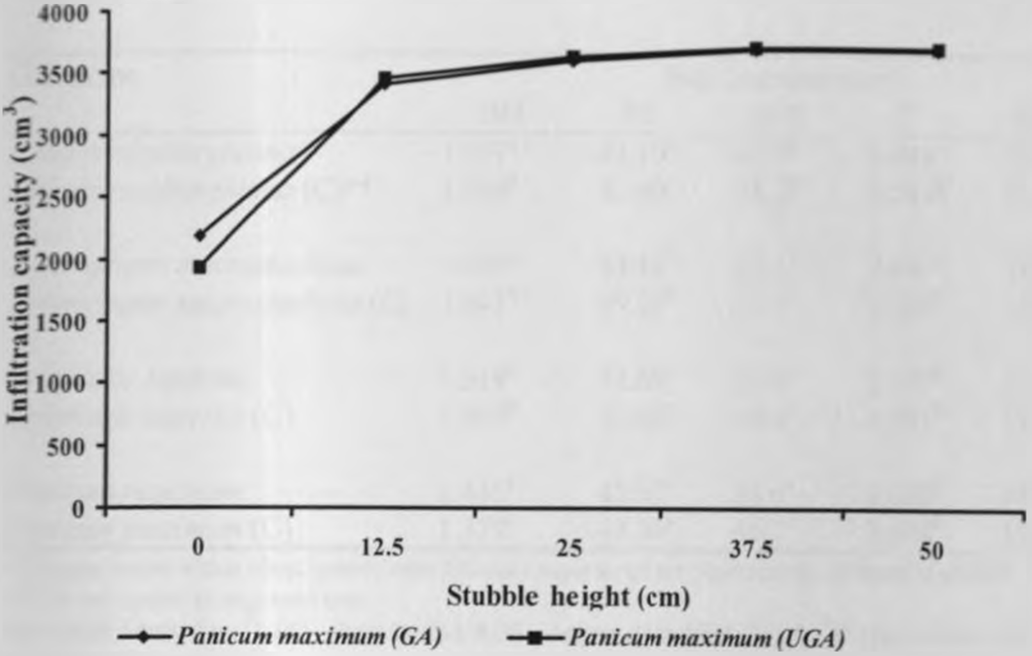


Figure 4.20. Infiltration capacity curves for *Panicum maximum* sites when grazed (GA) and ungrazed (UGA)



The soil physical characteristics under the various grass stands in the grazed and ungrazed area are presented in Table 4.18. Generally, the grass stands protected from grazing recorded favourable soil physical properties for enhanced infiltration capacity. Grass stands in the ungrazed areas had higher porosity, aggregate stability and organic carbon and lower bulk density compared to those in the grazed areas. Aggregate stability (AGS) and percent organic carbon (C), and percent cover (CR) were the most significant ($p<0.05$) soil and plant attributes that influenced infiltration capacity, respectively (Table 4.19). The predictive equation for infiltration capacity based on Ordinary Least Squares (OLS) for the area is given by the following equation:

$$10(\text{Infiltration capacity}) = 2.94AGS + 2.73C + 5.15CR, R^2=0.83$$

Table 4.18. Soil physical characteristics under various grass stands in grazed and ungrazed sites

Grass type	Soil characteristic*				
	BD	PO	AGS	C	SMC
Chloris roxyburghiana	1.557^a	41.10^a	42.8^a	2.416^a	20.20^a
Chloris roxyburghiana (C)**	1.549^a	41.40^a	48.2^b	3.217^b	21.35^a
Enteropogon macrostachyus	1.505^a	43.30^a	25.1^a	2.631^a	16.29^a
Enteropogon macrostachyus (C)	1.343^a	49.20^a	37.5^b	3.369^b	17.01^a
Eragrostis superba	1.519^a	42.60^a	31.8^a	2.195^a	16.68^a
Eragrostis superba (C)	1.499^a	43.40^a	36.4^b	3.041^b	18.51^a
Panicum maximum	1.445^a	45.50^a	38.6^a	2.078^a	18.24^a
Panicum maximum (C)	1.339^a	49.30^a	46.2^b	3.608^b	19.15^a

*Column means within plant species with different superscript are significantly different at $p<0.05$

**C is the control in ungrazed area

BD - Bulk density (gm^{-3}), PO - Porosity (%), AGS - Aggregate stability (%), C - Organic carbon (%), SMC - Soil moisture content (%)

Table 4.19. Regression analysis and factors influencing infiltration capacity

Variable	β	Significance	VIF*
Constant	-	0.061	-
Bulk density	0.113	0.398	1.758
Aggregate stability	0.294	0.033	1.579
Organic carbon	0.273	0.049	1.644
Cover	0.515	0.043	5.500
Standing crop	0.203	0.369	4.975
Soil moisture content	-0.027	0.820	1.472

*A factor with a Variance Inflation Factor (VIF) value of less than 10 is acceptable to be included in the regression analysis. Above 10, problems of multicollinearity arise (Gujarati 1995)

Panicum maximum and *Enteropogon macrostachyus* stood out as the most suitable perennial grasses, with favourable soil physical properties and infiltration capacity. These grasses also gave lower runoff and sediment loss.

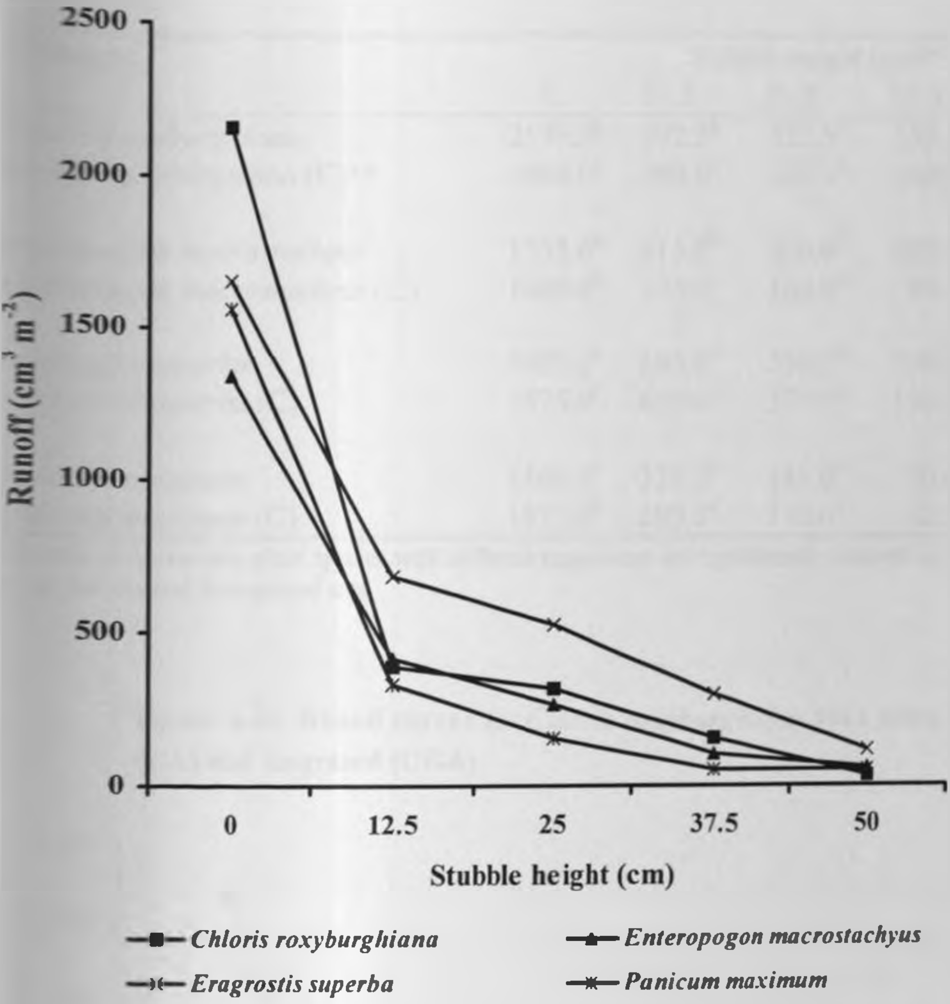
The runoffs (cm^3m^{-2}) of sites with four perennial grasses at various stubble heights are shown in Table 4.20 and illustrated in Figure 4.21. Grasses with higher and lower infiltration capacities gave lower and higher runoffs, respectively. Thus, *Panicum maxmum* yielded significantly ($p<0.05$) lower runoff between 12.5 to 37.5cm stubble height, followed by *Enteropogon macrostachyus*, *Chloris roxyburghiana* and *Eragrostis superba*.

Table 4.20. Runoff (cm^3m^{-2}) from grazed sites dominated by four perennial grasses at various stubble heights

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	2155.0^a	392.5^a	322.5^a	155.0^a	35.0^a
Enteropogon macrostachyus	1335.0^b	415.0^a	270.0^b	105.0^b	60.0^a
Eragrostis superba	1650.0^c	685.0^c	530.0^c	300.0^c	117.5^b
Panicum maximum	1560.0^d	335.0^d	155.0^d	50.0^d	50.0^a

*Column means with different superscript are significantly different at $p<0.05$

Figure 4.21. Runoff curves for grazed sites dominated by perennial grasses at various stubble heights



Similarly, the grasses in the grazed area gave higher runoff than the controls (Table 4.21 and Figures 4.22, 4.23, 4.24 and 4.25). For all the perennial grasses, runoff increased rapidly below 25cm stubble height. This indicated that reducing the stubble height beyond the 50% threshold undermines the protective function of the grasses to the environment.

Table 4.21. Runoff (cm^3m^{-2}) from grazed and ungrazed sites dominated by four perennial grasses at various stubble heights

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	2155.0^{b}	392.5^{b}	322.5^{b}	155.0^{a}	35.0^{a}
Chloris roxyburghiana (C)**	1860.0^{a}	360.0^{a}	235.0^{a}	140.0^{a}	30.0^{a}
Enteropogon macrostachyus	1335.0^{a}	415.0^{b}	270.0^{b}	105.0^{a}	60.0^{a}
Enteropogon macrostachyus (C)	1400.0^{b}	325.0^{a}	160.0^{a}	95.0^{a}	50.0^{a}
Eragrostis superba	1650.0^{b}	685.0^{b}	530.0^{b}	300.0^{b}	117.5^{a}
Eragrostis superba (C)	1575.0^{a}	620.0^{a}	375.0^{a}	155.0^{a}	95.0^{a}
Panicum maximum	1560.0^{a}	335.0^{b}	155.0^{b}	50.0^{a}	50.0^{a}
Panicum maximum (C)	1825.0^{b}	295.0^{a}	110.0^{a}	42.5^{a}	40.0^{a}

*Column means within plant species with different superscript are significantly different at $p<0.05$

**C is the control in ungrazed area

Figure 4.22. Runoff curves for *Chloris roxyburghiana* sites when grazed (GA) and ungrazed (UGA)

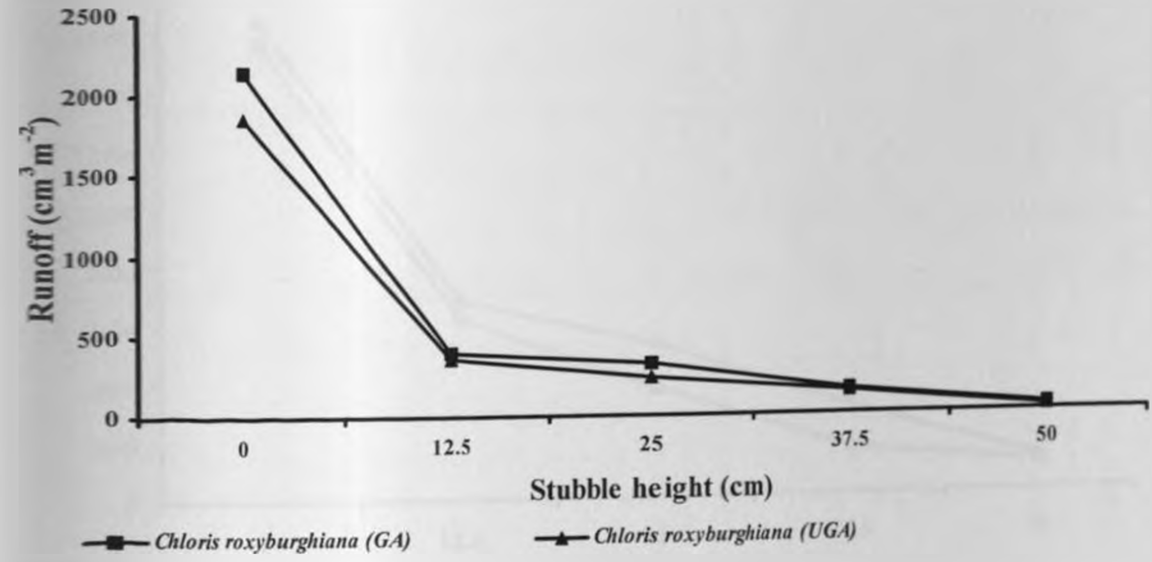


Figure 4.23. Runoff curves for *Enteropogon macrostachyus* sites when grazed (GA) and ungrazed (UGA)

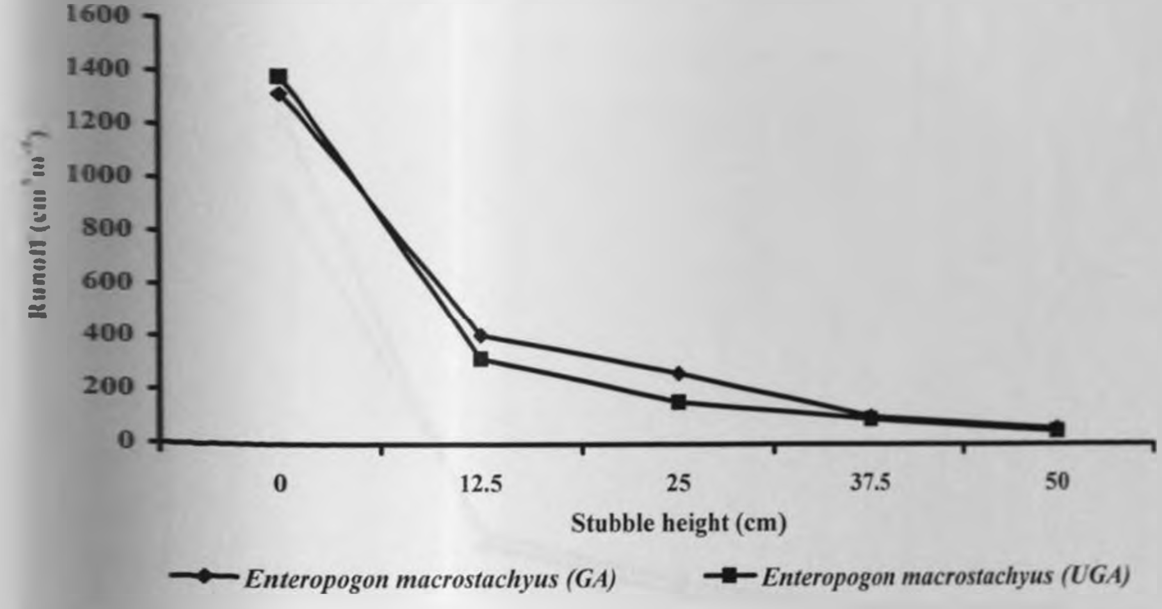


Figure 4.24. Runoff curves for *Eragrostis superba* sites when grazed (GA) and ungrazed (UGA)

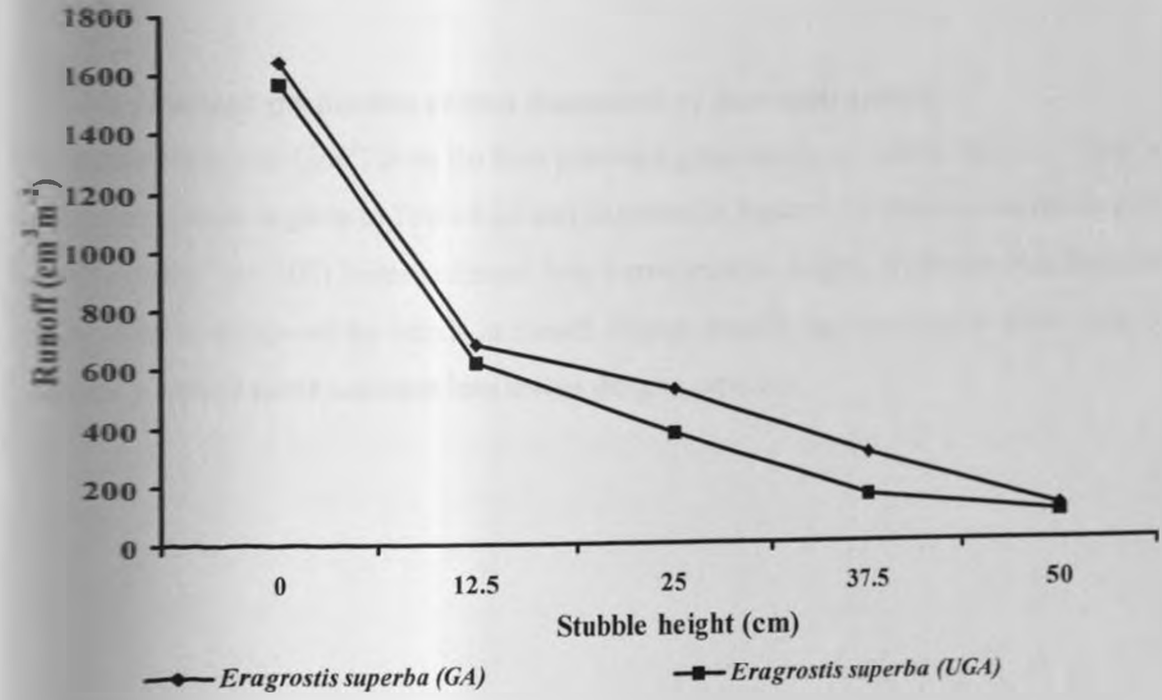
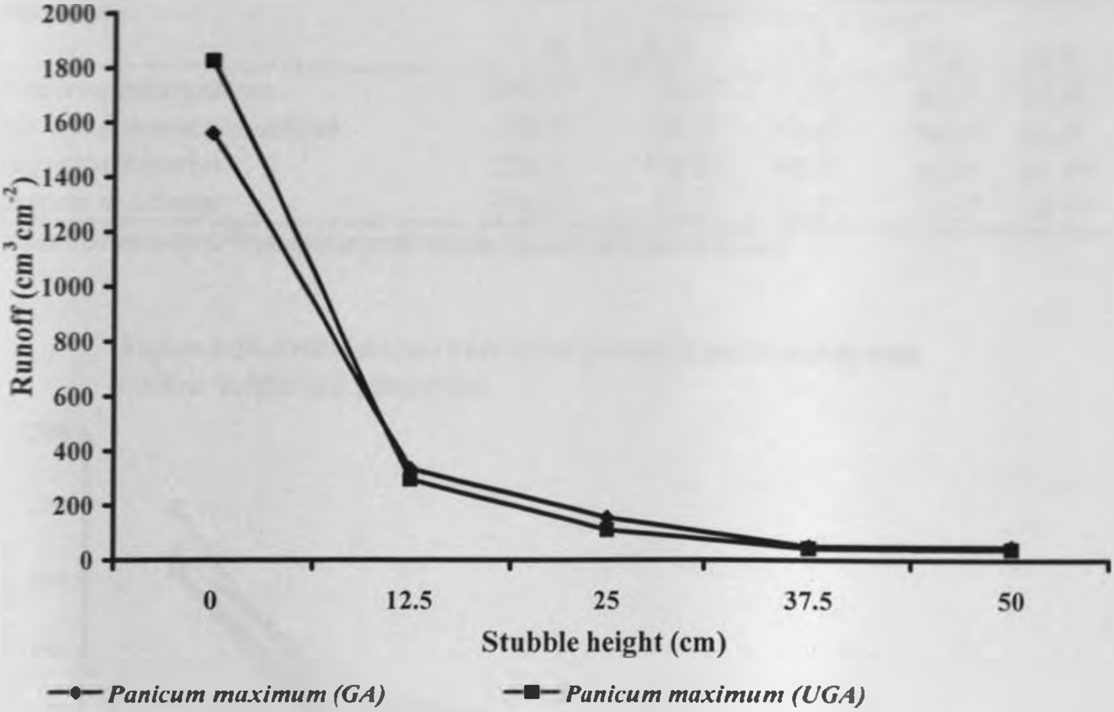


Figure 4.25. Runoff curves for *Panicum maximum* sites when grazed (GA) and ungrazed (UGA)



4.9.2. Sediment production of sites dominated by perennial grasses

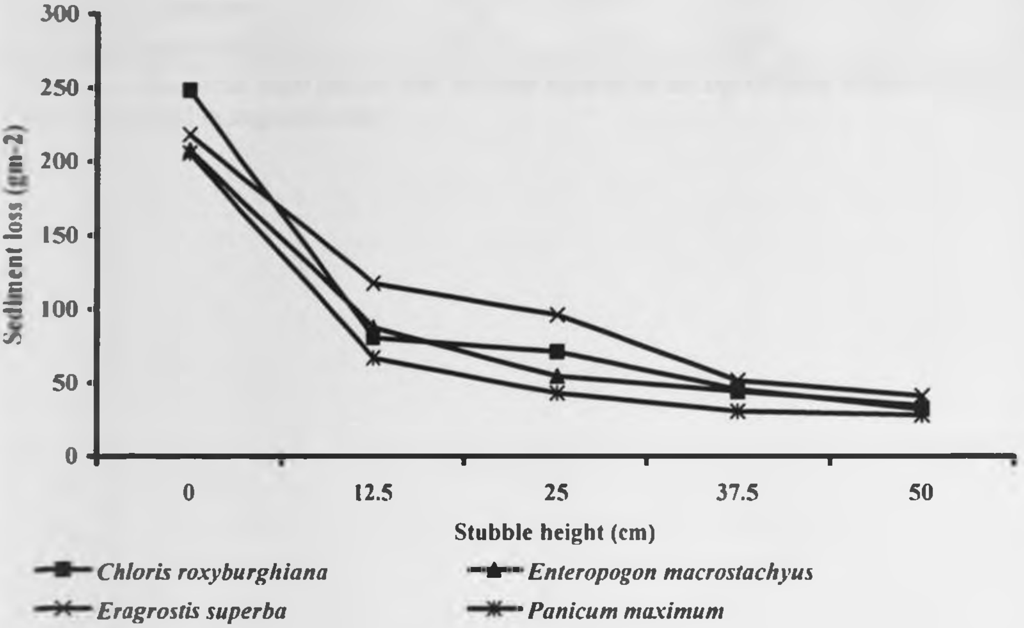
The sediment loss (gm^{-2}) from the four perennial grass stands at various stubble heights in the grazing area is given in Table 4.22 and illustrated in Figure 4.26. *Panicum maximum* gave significantly ($p<0.05$) lower sediment loss across stubble heights. Sediment loss from the grass stands followed the trends in runoff. Higher runoffs that occurred at lower stubble heights yielded more sediment loss across the grass species.

Table 4.22. Sediment loss (gm^{-2}) from four perennial grass stands at various stubble heights in a grazed site

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	248.5^{a}	81.0^{a}	71.5^{a}	46.0^{a}	32.5^{a}
Enteropogon macrostachyus	208.0^{b}	88.0^{a}	55.0^{b}	44.5^{a}	35.0^{a}
Eragrostis superba	218.5^{c}	118.0^{b}	96.5^{c}	52.0^{a}	41.5^{ac}
Panicum maximum	206.0^{b}	67.5^{d}	43.5^{d}	31.0^{b}	28.5^{ab}

*Column means with different superscript are significantly different at $p<0.05$

Figure 4.26. Sediment loss curves for perennial grass stands with stubble height in a grazed site



Grass stands in the grazed area also gave significantly ($p<0.05$) higher sediment loss than in the ungrazed area (Table 4.23 and Figures 4.27, 4.28, 4.29 and 4.30). This could be attributed to the deleterious effects of grazing (Van de koppel *et al.* 1997). Grazing reduces the soil surface protective cover, and in other cases, the hoof action tends to loosen soil particles, allowing raindrops to directly pound the soil surface and easily wash off soil particles. This then leads to increased sediment loss.

Table 4.23. Sediment loss (gm^{-2}) from four perennial grass stands at various stubble heights in grazed and ungrazed sites

Grass type	Stubble height (cm)*				
	0	12.5	25.0	37.5	50.0
Chloris roxyburghiana	248.5^{b}	81.0^{a}	71.5^{b}	46.0^{b}	32.5^{b}
Chloris roxyburghiana (C)**	167.5^{a}	70.5^{a}	38.5^{a}	28.5^{a}	16.0^{a}
Enteropogon macrostachyus	208.0^{b}	88.0^{b}	55.0^{b}	44.5^{a}	35.0^{b}
Enteropogon macrostachyus (C)	169.0^{a}	54.0^{a}	33.0^{a}	26.5^{a}	15.5^{a}
Eragrostis superba	218.5^{b}	118.0^{b}	96.5^{b}	52.0^{b}	41.5^{b}
Eragrostis superba (C)	183.0^{a}	80.0^{a}	53.0^{a}	35.5^{a}	20.5^{a}
Panicum maximum	206.0^{b}	67.5^{b}	43.5^{b}	31.0^{a}	28.5^{b}
Panicum maximum (C)	133.5^{a}	37.5^{a}	26.0^{e}	21.5^{a}	15.0^{a}

*Column means within plant species with different superscript are significantly different at $p<0.05$

**C is the control in ungrazed area

Figure 4.27. Sediment loss curves for *Chloris roxyburghiana* stand in grazed (GA) and ungrazed (UGA) sites

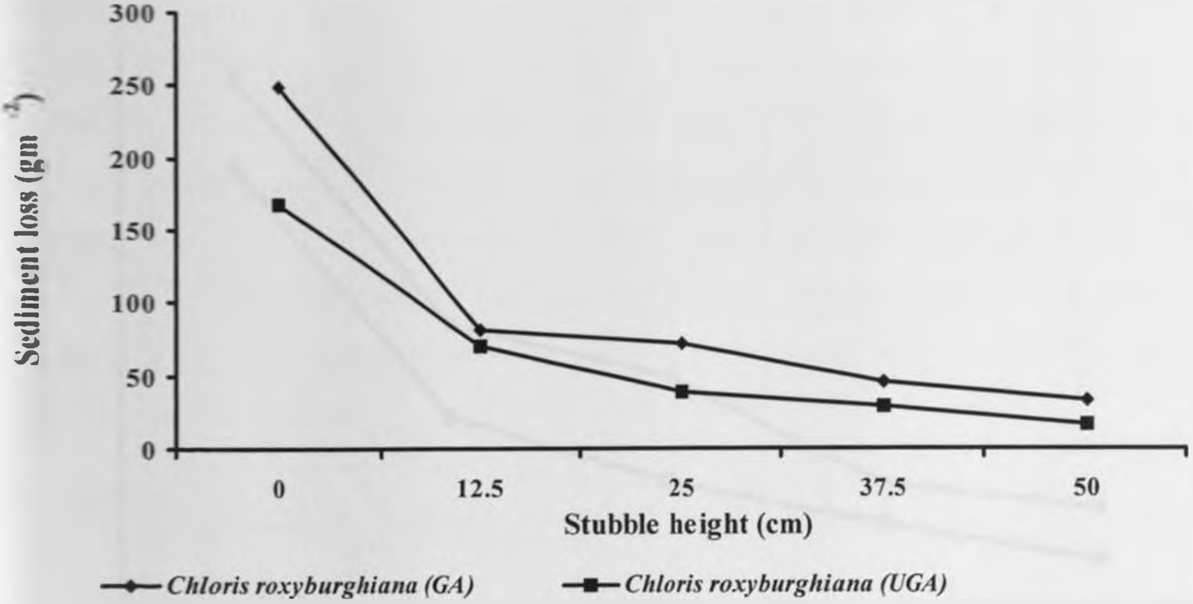


Figure 4.28. Sediment loss curves for *Enteropogon macrostachyus* stand in grazed (GA) and ungrazed (UGA) sites

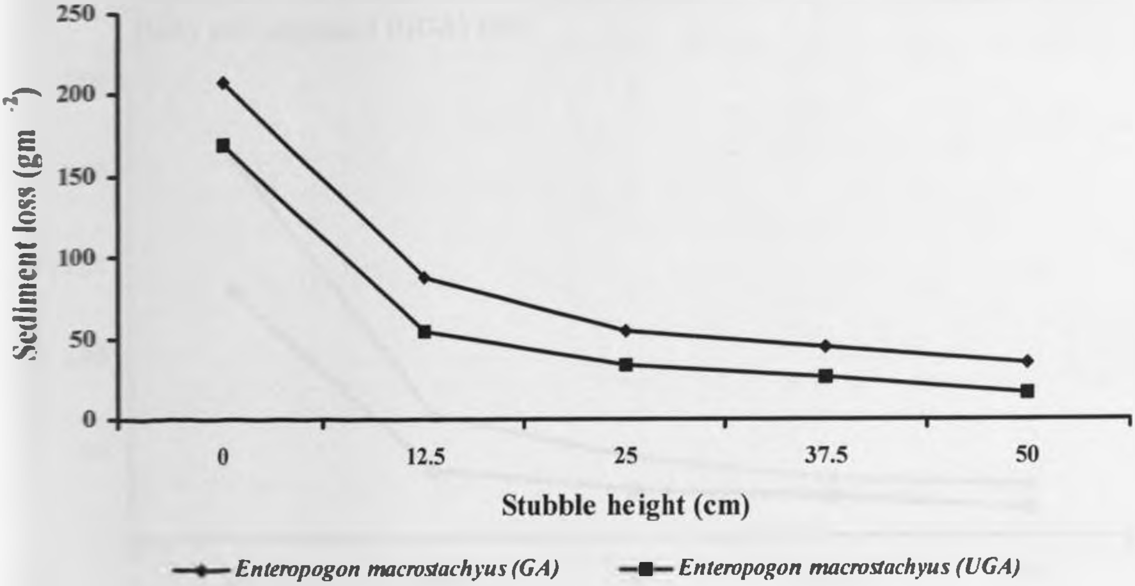


Figure 4.29. Sediment loss curves for *Eragrostis superba* stand in grazed (GA) and ungrazed (UGA) sites

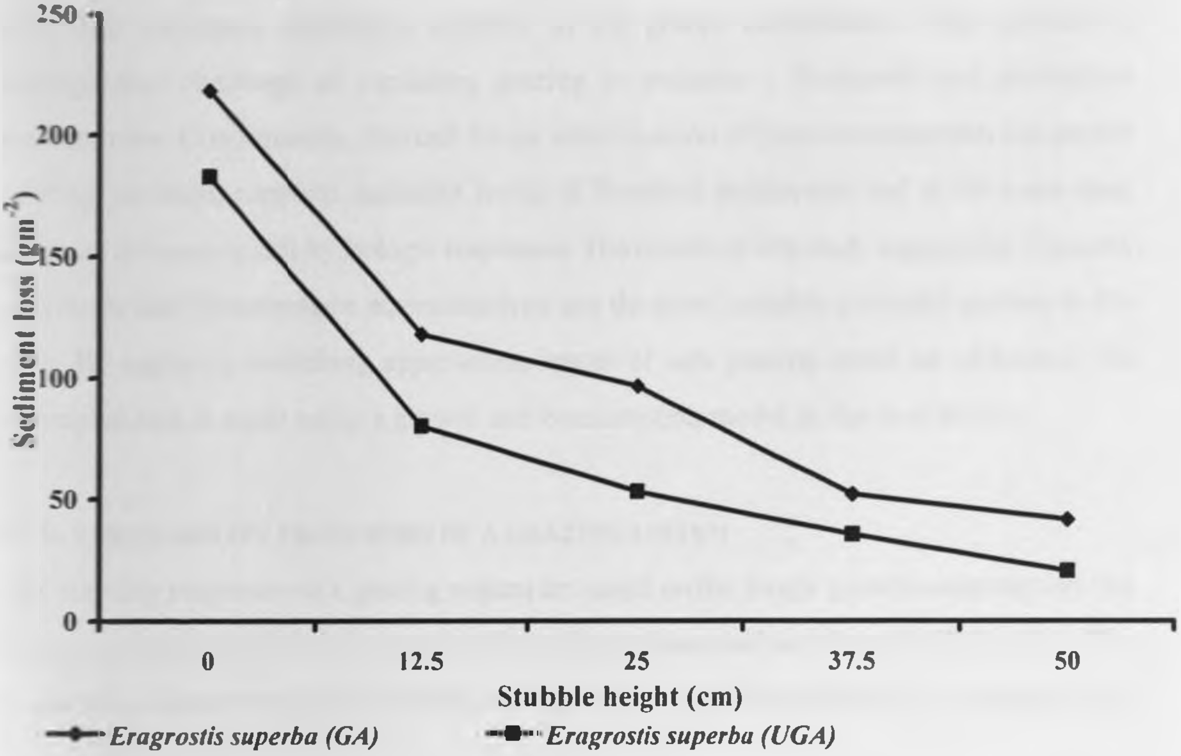
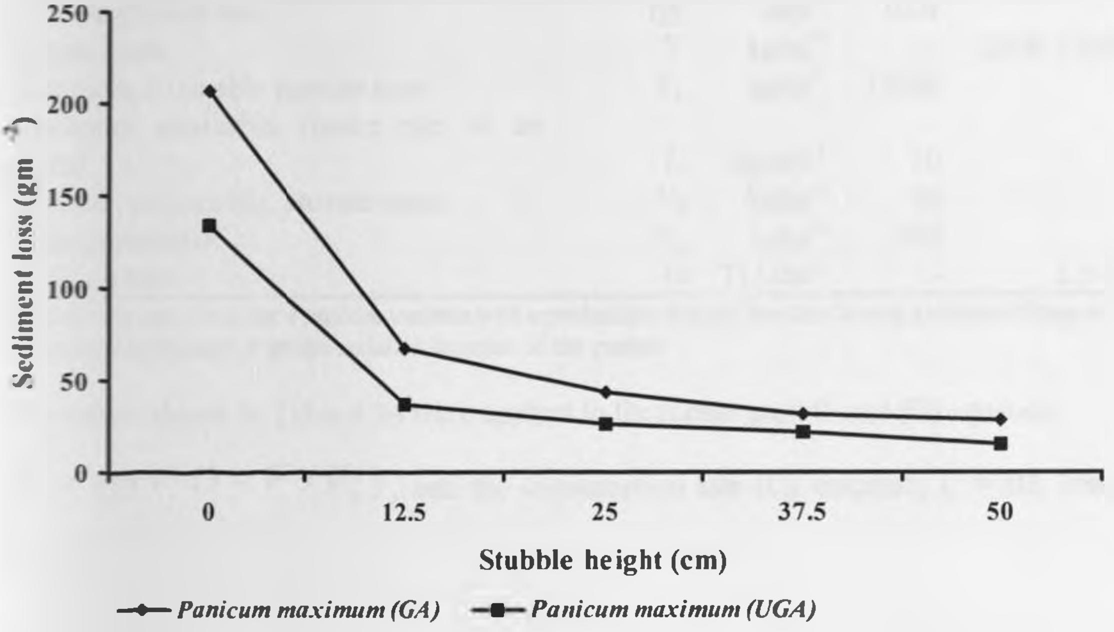


Figure 4.30. Sediment loss curves for *Panicum maximum* stand in grazed (GA) and ungrazed (UGA) sites



The results on hydrological responses of the perennial grasses attest to the fact that long term grazing negatively affects soil physical properties, leading to increased runoff and sediment loss. and decreased infiltration capacity in the grazed environment. This presents a management challenge of regulating grazing to maintain a favourable and productive environment. Consequently, this call for the identification of plant resources that can persist grazing pressure, supports desirable levels of livestock production and at the same time enhance favourable soil hydrologic responses. The results of this study suggest that *Panicum maximum* and *Enteropogon macrostachyus* are the most suitable perennial grasses in the area. By applying modelling approaches, issues of safe grazing could be addressed. An attempt at this is made using a growth and consumption model in the next section.

4.10. THE STABILITY PROPERTIES OF A GRAZING SYSTEM

The stability properties of a grazing system are based on the forage growth-consumption rate model. The parameters of the model and standard values used are shown in Table 4.24. The standard values used are those calculated from data on semiarid pastures by Noymeir (1978).

Table 4.24. Parameters (and their values) used in growth-consumption rate model

Parameter	Symbols	Units	Value	Range-tested
Relative growth rate	rgr	day^{-1}	0.04	-
Pasture mass	V	$kgha^{-1}$	-	2000-12000
Maximum attainable pasture mass	V_x	$kgha^{-1}$	12500	-
Maximum attainable intake rate of an animal	I_x	$kgday^{-1}$	10	-
Residual, ungrazable, pasture mass	V_r	$kgha^{-1}$	50	-
Shape parameter*	V_s	$kgha^{-1}$	500	-
Stocking rate	H	$TLUha^{-1}$	-	2.5-10

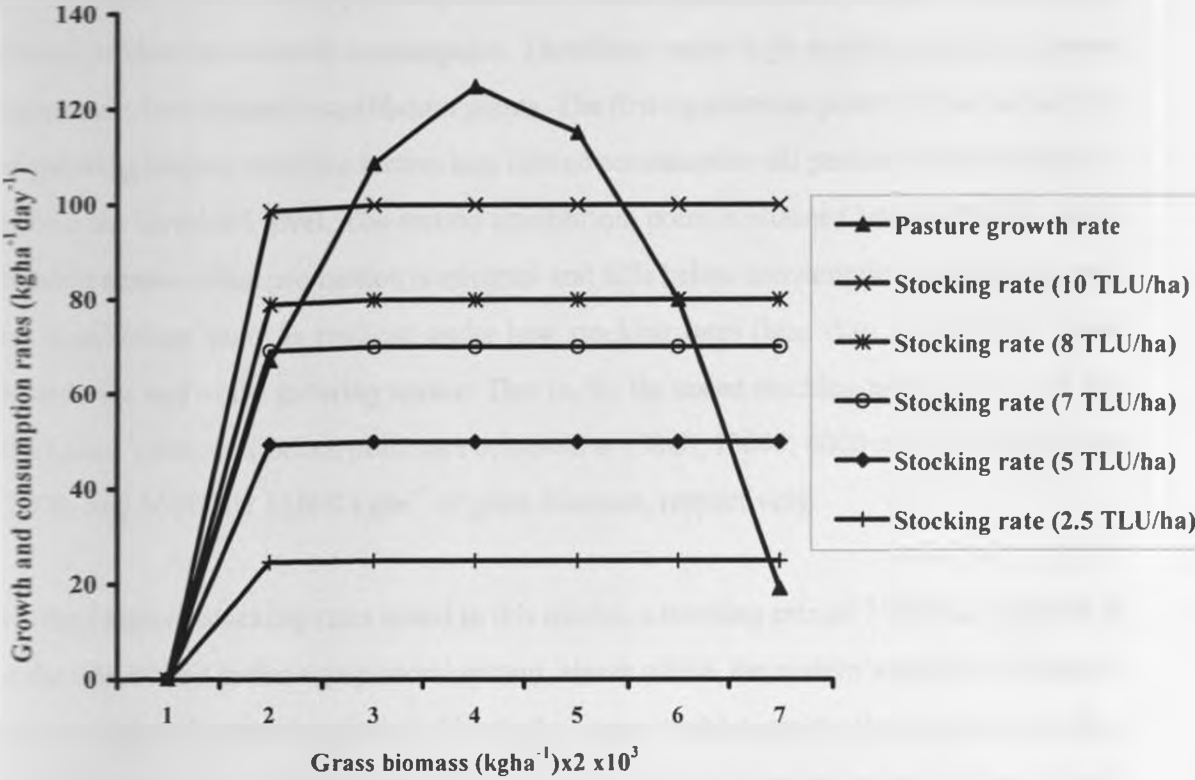
*Defines the best curve for a random variable with a probability density function having a variety of shapes. In this case, it is attained at intake-satiation biomass of the pasture

The values shown in Table 4.24 were applied to the forage growth rate (G) equation, $G = rgrV\ (1 - V / V_x)$, and the consumption rate (C) equation, C = IH, where

$$I = I_x(1 - e^{-\frac{V - V_r}{V_s - V_r}}).$$

The outputs of the model are illustrated graphically in Figure 4.31.

Figure 4.31. Growth/consumption relationships under five stocking rates



As shown in Figure 4.31, grass growth rate initially increases rapidly, then gradually to a maximum before beginning to decelerate to zero as the end of the growing season approaches. Consumption rates generally increase with growth rate till the maximum satiation intake, that is, intake at which consumption is saturated. For the stocking rates presented, that is, 2.5, 5.0, 7.0, 8.0 and 10 TLUha^{-1}, satiation intake is achieved at 25, 50, 70, 80 and 100 kgha^{-1}day^{-1}, respectively.

At low stocking rates, in this case, up to 5 TLUha^{-1}, consumption rate lags behind pasture growth rate. Therefore, at any point in the grazing system in this case, pasture production is in excess of consumption and there is minimal grazing damage to the system. Grazing damage is only likely late in the growing period when there is minimal pasture production. At higher stoking rates, in this case, above 7 TLUha^{-1}, pasture growth rate initially lags behind consumption rate. Under this scenario, grazing damage is expected as pasture consumption is in excess of pasture production. Grazing damage only stops at points where pasture production exceeds consumption. Therefore, under high stocking rates the system experiences two dynamic equilibrium points. The first equilibrium point is observed early in the growing season when production lags behind consumption till pasture mass accumulates beyond the threshold level. The second equilibrium point is attained later at the end of the growing season when production is minimal and falls below consumption. In contrast, only one equilibrium point is realized under low stocking rates (less than 5.0 TLUha^{-1}) later towards the end of the growing season. That is, for the tested stocking rates, 2.5, 5, 7, 8 and 10 TLUha^{-1}, the equilibrium points are achieved at 13800, 13000, 4000 and 12300, 4600 and 12000, and 5600 and 11000 kgha^{-1} of grass biomass, respectively.

For the range of stocking rates tested in this model, a stocking rate of 7 TLUha^{-1} appears to be the upper limit in this agropastoral system, above which, the system's stability is likely to cave in during the growing period. This is the range at which production and consumption closely match from the beginning till later on in the growing period when production exceeds consumption. To operate above the critical limits, where consumption exceeds production, without affecting the stability of the system, it will require management strategies that take-off the grazing load till pasture production exceeds consumption. The options available include destocking, supplementary feeding, and deferment with reserve pastures located within the system absorbing the grazing load. Destocking, where livestock is the main livelihood source is usually unattractive. Also, supplementary feeding, particularly with bought supplements can be quite challenging to resource poor agropastoralists. This leaves resource poor agropastoralists with only two options of using non-conventional supplements and seeking reserve grazing within the system. The non-conventional supplements used are mainly crop residues whose production is seriously undermined by the high risk of crop failure reported in this system. On the other hand, reserve grazing that may have existed outside the system is now no longer available as these areas are currently protected as game reserves.

Given the limited farm sizes in this system (about 8 acres for 58% of the households), few agropastoralists can afford to create grazing reserves. The grazing areas are largely used throughout the year. Therefore, faced with inadequate pastures, the agropastoralists engage in informal arrangements or secondary grazing land rights, as the only feasible alternative to accessing extra grazing. The next chapter analyses the household characteristics and factors that influence the use of secondary grazing rights in the study area.

CHAPTER FIVE: RESULTS AND DISCUSSION

SECONDARY LAND RIGHTS

5.1. HOUSEHOLD STRUCTURE AND SECONDARY LAND RIGHTS

Descriptive analysis showed that, in Kibwezi, 76% of the households are male headed, while 24% are female headed (Table 5.1). The household heads were expected to be responsible for all decisions made at household level. However, in terms of decision-making, females accounted for 20% of all decisions made on the herd and farm activities at household level.

Table 5.1. Household structure and secondary grazing rights status

Characteristic	% of households*
Household headship and decision making	
Male-headed house households	76
Percent decision making by males	80
Female-headed households	24
Percent decision making females	20
Level of education of decision makers at household level	
Up to primary level	68
Secondary level	18
College level	14
Mean land size per household (acres)	8
Tenure and/user right on grazing lands	
Permanent/individual user right	98
Temporary/individual user right	2
Dry season fields	62
Use of secondary rights	
Short term loan (<1yr)	64
Exchange of labour	6
Exchange of bulls to plough	38
Participation of institutions to enforcing secondary rights	
Council of village elders	94
Chiefs	28
Tenure rights and policies for good land management	
Permanent and individual user rights	72
Permanent and communal user rights	24

*sample size (N) = 50

The variation in percentage of females making decisions at household level compared to that of heading the household is attributed to elder sons stepping in and taking responsibility for decision-making. These results suggest that the Kamba agropastoralists of Kibwezi are strongly patrilineal.

Sixty eight percent of the decision makers at household level have primary level education. This indicates that a majority of the decision makers rely on life experiences than formal education to make decisions.

Fifty eight percent of the households in Kibwezi have less than 15 acres of land, with a median of 8 acres. The land is owned under freehold and permanent individual user rights. This land sizes are small for a semiarid environment. The small land sizes are unlikely to sustain meaningful livelihoods in light of increasing human population and the variable environment that is often dry. Future sustainability in production will therefore require adoption of land tenure rights that are flexible to allow households that are land constrained to access the land belonging to others but not in effective use.

Tenure rights on grazing resources are particularly practised and enforced in the dry season. Sixty two percent of the households in Kibwezi exercise tenure rules and user rights on dry season fields. This is a strategy to secure pasture availability during the most critical period of pasture scarcity. Seventy percent of the households use a number of secondary rights to secure pasture for their animals, particularly short term loans (64%) and exchange of bulls for ploughing (38%). These secondary rights give them flexibility in dealing with pasture shortages during critical periods. Also, they allow the households to adjust to changing scenarios in the production system. The wide range of secondary rights used in the production system suggest that their use is entrenched. Thus, the challenge of producing in a land-limited and variable environment has necessitated the evolution of such coping strategies to sustain livelihoods.

The council of village elders still remains an important institution for arbitrating land tenure issues. Among the Kamba of Kibwezi, the institution accounts for 94% of the cases settled. However, this institution is threatened by rapid modernization and social differentiation in this society. To enhance the capacity of such institutions, most respondents suggested that they should be recognized by the government, be entrenched in the constitution and that the elders should be trained to appreciate the current laws and policies under which land tenure and land transactions operate. That way, the elders are likely to make enlightened decisions and the decisions will be binding. Seventy two percent of the households considered land tenure and policy interventions that promote permanent, private and individual use rights of land and pasture as suitable for good land management. This is in agreement with the theory that upholds that private ownership maximizes private gains and thus encourages households to use resources in a conserving manner. However, as land sizes become smaller and pasture availability declines, cases of land degradation increase and people prefer pooled grazing resources, suggesting a controlled communal property rights regime.

5.2. USE OF SECONDARY LAND RIGHTS BY HOUSEHOLDS

This section explains differences in households in using secondary land rights to secure grazing for their livestock using variables for which data are available. Households were stratified *a posteriori* by age of household head, level of education of household head, and stocking rate per household. The stocking rate was assumed to be an encompassing factor that is influenced by farm size per household, grazing area available per adult equivalent per household, total tropical livestock unit per household, tropical livestock unit per adult equivalent per household, and available crop residues per household.

The households were then subdivided into three groups: lower tercile (implying low use of secondary land rights), middle tercile, and upper tercile (implying high use of secondary land rights). The values of the variables for the extreme groups, the 'lowest' and the 'highest', are reported to clearly bring out any differences.

The indicator variables used for the analysis were selected for various reasons. Age is an important indicator of the status of the household head with respect to ownership and control of household resources. Also, one's responsibilities, including decision making at household level, are likely to increase with age. Therefore, the age of the household head can be used to gauge how one is regarded and upheld to transact on behalf of the household. In terms of age, the household heads were grouped into three classes, that is, less or equal to 40 years (lower tercile), 41 to 50 years (middle tercile), and equal to or greater than 51 years (upper tercile).

The level of education of the household head is a useful indicator as it reflects awareness and ability to make beneficial decisions for the household. An educated person is more likely to understand the operational circumstances of the household and would be more judicious in the use of secondary land rights to enhance livestock keeping or shift to other activities that can enhance the livelihood base of the household. For example, a highly educated household head may not depend on livestock farming, but may opt out and seek salaried employment. Therefore, the household heads were classified as: up to primary level (low tercile), secondary level (middle tercile), and college level (upper tercile).

The stocking rate determines the quantity and quality of grazing available to the livestock. When the stocking rate is low, the quantity/quality of grazing is high and there is no need to use secondary land rights, as the household is likely to be self-reliant. The converse is true, that is high stocking rates accompanied by low quality and low availability of grazing, would necessitate the household to seek quality grazing and acquire more grazing by employing secondary land rights. Therefore, the households were classified into the three classes using a stocking rate of 6 to 10 acres per tropical livestock unit as the middle tercile (the recommended conservative stocking rates throughout the grazing cycle for semiarid areas (Pratt and Gwynne 1977)), below 6 acres per tropical livestock unit as the upper tercile and above 10 acres per tropical livestock unit as the lower tercile.

Both age and stocking rate had more persons practising secondary land rights in the upper tercile than the lower one (Table 5.2). This implied that increasing age and stocking rate positively influenced use of secondary land rights to acquire extra grazing by households. On the other hand, based on the level of education, there were more households practising secondary land rights in the lower tercile than the upper one. This indicated that increasing the level of education of the household heads negatively influenced practising secondary land rights. This could be attributed to higher education enabling household heads to diversify their livelihood strategies. The net effect of diversifying livelihood strategies is reduction of the households' reliance on livestock keeping.

Table 5.2. Differences (or similarities) between the lower and upper terciles in Kibwezi

Characteristic	Lower tercile	Middle tercile	Upper tercile
Age	26	40	34
Level of education	69	13	14
Stocking rate	3	3	94

5.3. FACTORS INFLUENCING USE OF SECONDARY LAND RIGHTS

The results just discussed though informative have limitations partly because the use of terciles does not determine the significance of the variables, as the analysis is purely descriptive. Also, classifying variables into terciles based on generally acceptable criteria cannot be extended to all factors. Despite the difficulties that arise regarding the use of household survey data, econometric analysis offers an opportunity for assessing the level of influence exerted by these factors. It also enables the inclusion of a wider range of factors that would otherwise not be appropriate in the analysis of terciles. The discussion that follows is based on a multivariate regression analysis using the Wald test statistic that can be applied to both linear and non-linear regressions. This analysis allows the estimation of a regression model that describes the household factors significantly influencing the use of secondary land rights to access extra grazing by the households.

The response to secondary land rights to alleviate grazing pressure is modelled as a dichotomous variable, which takes a value of one if the herder/household practises them or zero if not. The logit framework is applied to estimate the significance of the various variables as earlier described. Table 5.3 gives a summary of the hypothesized explanatory variables tested in the multivariate model that influence practising secondary land rights. The model was estimated using the SPSS 11.6 statistical package and the significance of the results was tested using the Wald test (W).

Table 5.3. Summary definitions and range of variables tested

Variable	Definition	Range tested	Median	Mean
FS	Farm size per household (acres)	1.5-75	13.25	19.51
FS/AE	Farm size per adult equivalent in the household	0.33-16.44	2.34	3.23
GA	Grazing area per household (acre)	0.5-37.5	4.0	8.26
CROP	Crop area per household (acre)	1.0-40	8.0	11.23
TLU/AE	Tropical livestock units per adult equivalent	0.2-8	1.05	1.45
TLU/HH	Tropical livestock units per household	1.0-26	7.0	7.96
AGE(1)	Age of household head (31-40 years) (yes=1, no=0)	31-40	-	-
AGE(2)	Age of household head (41-50 years) (yes=1, no=0)	41-50	-	-
AGE(3)	Age of household head (≥51 years) (yes=1, no=0)	≥51	≥51	≥51
LEDU	Level of education attained by household head	-	-	-
LEDU(1)	Up to primary level of education (yes=1, no=0)	-	-	-
LEDU(2)	Secondary level of education (yes=1, no=0)	-	2	2
LEDU(3)	College level of education (yes=1, no=0)	-	-	-
SHOATS:COW*	Number of goat and sheep to cows ratio	0.3-22	4.85	4.85
GA/AE	Grazing area per adult equivalent in the household (acre)	0.08-8.67	0.69	1.37
RES	Crop residue available for feeding animals (tons)	0-160	21	30.9
GENDER	Gender (female=0, male= 1)	-	1	1
SR	Stocking rate in acre per tropical livestock unit	0.07-13.75	2	3.4
AE	Adult equivalent (Children of 16 years = 0.5 adult equivalent)	2.5-18.5	5.5	6.22

*7 shoats = 1cow = 1TLU = 250kgs

Table 5.4 presents the results of the logistic regression, which predict the use or non-use of secondary land rights from a number of continuous and dummy variables. As shown in Table 5.4, farm size per adult equivalent is significant at 5% level and exerts a large positive effect on the use of secondary land rights to access pasture. Age, amount of crop residue available, and grazing area per adult equivalent are important at 5% and have a negative effect. Tropical livestock unit per adult equivalent and small stock (goats and sheep) to cow ratio are important at 10% level and exert a positive effect.

Table 5.4. Regression analysis and factors influencing use of secondary land rights

Variable	Coefficient (β)	Wald	Exp(β)
FS/AE	3.126	5.454**	22.772
TLU/AE	1.405	3.061*	4.076
AGE	-	4.564	-
AGE1)	-3.591	4.355**	0.028
AGE(2)	-1.713	1.197	0.180
LEDU	-	5.286	-
LEDU(1)	2.645	1.621	14.087
LEDU(2)	1.160	0.602	3.191
LEDU(3)	-2.098	1.472	0.123
SHOATS:COW	0.228	3.149*	1.256
GA/AE	-4.406	6.297**	0.012
RES	-0.105	4.300**	0.901
GENDER	1.215	0.390	3.371
SR	0.539	2.814*	0.583
CONST	-0.629	0.048	0.533

** Significant at 5% level; * Significant at 10% level
-2log likelihood = 30.99; Chi-square = 30.10

In the agropastoral setting of Kibwezi, farm size has a positive effect on the use of secondary land rights. Increasing farm size increases the grazing land available and therefore affords the herders the opportunity to employ secondary land rights to access grazing of high quality. That is, whereas the herds could stay on the household land, continuous grazing reduces the quality of available grazing and livestock productivity. This encourages the herders to use secondary land rights to access quality grazing in underutilized farms belonging to different households and thus maintain livestock productivity. However, when the grazing area available is large enough to avoid compromising grazing quality with use, increasing grazing area, as indicated by grazing area available per adult equivalent, has a negative effect on the use of secondary land rights.

Decreasing age of the household head has a significant negative effect on the use of secondary land rights in the agropastoral community. As indicated earlier, household decision-making, resource ownership and use are usually bestowed on older persons. This enhances the status of older persons and presents them with the opportunity to transact on behalf of the household. Also, the security of secondary land rights is largely based on trust, which is earned with increasing age. This suggests that there is confidence in dealing with older people, and therefore the use of secondary land rights increases with age because of the associated security.

As expected, increasing use of crop residues decreases the use of secondary land rights. Crop residues compensate for lost grazing to cropping. However, the small farm sizes (of about 13 acres, (the median is reported to avoid the impact of extreme values)) in Kibwezi makes it necessary for the herders to employ secondary land rights, as livestock units per adult equivalent increase. Increasing livestock units likely exceeds the compensation levels achieved by crop residues. This makes available livestock feed at household level insufficient, and therefore encourages increased use of secondary land rights.

Higher education has a negative effect on the use of secondary land rights. Higher education has the effect of empowering people to diversify their activities and thus livelihoods. It removes the pressure of depending on one livelihood strategy, and hence the negative impact. Increasing the number of smallstock (sheep and goats) relative to the number of large stock (cows) has a significant positive effect on secondary land rights. This could be attributed to the large surface area per unit body weight to volume ratio of smallstock. Because of this they consume more and thus require more grazing per unit of stock compared to large livestock.

From the above discussion, it is clear that in land constrained production systems like the agropastoral system of Kibwezi, increasing age of household head, farm size available per adult equivalent, smallstock to largestock ratio, and number of tropical livestock units exert a positive effect in the use of secondary land rights. Small farm sizes per adult equivalent (of about 2 acres) and the number of livestock units are central factors that determine animal feed supply-demand relationships. The positive effects of these factors on the use of secondary land rights suggest that secondary land rights play a critical role in stabilizing these relationships. Increasing amounts of crop residue and grazing area available dampen the use of secondary land rights as these factors ensure an abundant feed resource base. Since available grazing land will continue to decline with increasing population, expanding patterns of cultivation (currently taking about 67% of available land per household) and other activities that remove land from grazing, there is need to enhance the use of secondary land rights to access extra grazing.

Given the official policy towards land tenure that is geared to converting customary rights of access to individual tenure and exclusive property rights, there is need to create inbuilt flexibility in the tenure arrangements for herders to access critical grazing resources. Secondary land rights in resource allocation and use in rural subsistence systems could provide the desired flexibility to accessing key production resources.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1. GENERAL DISCUSSION

An understanding of the link between energy extraction patterns and intake by grazing ruminants is important in improving rangeland or grassland management systems so that factors which limit energy intake can be overcome. This suggests identifying the critical grazing resources that sustain livestock productivity in a given environment and quantifying the sward characteristics that need to be manipulated either in terms of optimal biomass, bulk density or other morphological composition so that energy intake can be optimized. Links between the utilization levels of forage resources and the attendant impacts on the grazing environment are important in determining grazing thresholds. All these aspects of energy extraction by grazing animals need to be clarified in the context of the social environment by which grazing strategies are dictated, particularly social arrangements that are instituted to determine and regulate grazing resource access and user rights.

In the studied system, the agropastoralists kept multispecies livestock that exploited a wide array of plant resources. These plant species have different phenologies and occupy different microsites, creating a spatial heterogeneity in food resources that attain peak production at different times. This spatial heterogeneity in food resources affords livestock the opportunity to occupy patches yielding the highest gain and also ensures that energy extraction and intake are stabilized over time. That is, both seasonality in vegetation growth and heterogeneity in resource type act to promote stability in energy supply (Owen-smith 1999). The animals tended to exploit transient forage resources early in the grazing cycle. For instance, annuals and early maturing plants were exploited more in the earlier parts of the grazing cycle followed by late producing perennials. This indicated that energy extraction patterns by grazing animals closely followed the annual relay cycle of the plants.

Two complementary energy pathways were identified in this study: herbaceous plants to grazers and woody plants to browsers. For the grazers, *Enteropogon macrostachyus* was the single largest energy pathway and accounted for over 30% of the total energy intake. The other important grass resources were *Panicum maximum* followed by *Eragrostis superba*. For the browsers, *Combretum exalatum* and *Duosperma kilimandscharica* were the main energy pathways and accounted for over 10% of total energy intake with seasonal peaks of 18.5 and 17.2%, respectively. These forage resources should be central to future evaluation and breeding efforts aimed at improving energy intake and livestock production in the area.

Central to energy intake at pasture is bite mass. Bite mass determines daily herbage intake. It is influenced by factors that determine bite dimensions, particularly sward structure and architecture. In this study, green bite weight for all livestock species declined from mid to late dry season, and increased from mid to late wet season. It averaged 0.13 to 0.17, 0.11 to 0.13, and 0.63 to 0.77g for goats, sheep and cattle, respectively, in the dry season. In the wet season, it ranged between 0.2 to 0.22, 0.15 to 0.17, and 0.89 to 0.97g for goats, sheep and cattle, respectively. Higher bite weights in the wet season compared to the dry season are in line with observed sward and tiller density in grazed pastures. Casey *et al.* (2004) observed increased bite mass with increasing bulk density of microswards for cattle. In the same study, bite mass declined with increasing tiller density.

Generally, sward bulk density is higher in the wet season, while tiller density is higher in the dry season, thus accounting for the observed differences in bite weights. Forage yield per bite for grazing animals is positively correlated with plant biomass per unit volume (Ludlow *et al.* 1982, Prins 1992). This is usually achieved in the growing period when plant biomass is increasing. In contrast, tiller density is associated with increasing shearing forces and thus reduced forage yield by bite (Illius *et al.* 1995). This is common in the dry season when tiller and stem mass increases in swards. These sward characteristics have important implications for sward management for enhanced livestock production.

Grazed swards should be managed for high bulk density leafy production with low stemmy tillers. Such swards should be utilized fully to avoid losses associated with advancing maturity. As swards mature, their nutritive quality declines because of decreasing digestibility. Optimal energy extraction is usually attained where the cropping and digestive constraint intersect (Shipley *et al.* 1999, Wilmshurst *et al.* 1999, 2000). Higher levels of optimal utilization could partly be sustained by breeding for leafy production and application of nitrogen fertilizers, or intercropping with legumes, to increase the nitrogen content of the swards.

The observed high overlap indices between livestock species, particularly during periods of resource scarcity, can present a serious management challenge. High overlaps during such periods are indicative of interspecific competition that can exacerbate the grazing pressure on available feed. High grazing loads can easily overshoot grazing thresholds with severe consequences to the grazing environment in terms resource of damage and degradation. Therefore, such shifts in grazing pressure must be factored-in in the grazing management so as to protect the environment. In this study, considering four perennial grasses, a 50% removal of current growth was the limit above which the protective functions of the grasses in the environment were undermined. Furthermore, using available data on a growth-consumption model, a stocking rate of 7 TLUha^{-1} appears to be the upper limit during the growing period.

The stocking levels (0.09-6 TLUha^{-1}) prevailing in the grazing areas of this study are within the calculated optimal stocking rate. This suggests that under the equilibrium-grazing paradigm, the grazing environment in the study area should not be degraded. Evidence from the pastoral and agropastoral grazing areas of eastern Africa point to the contrary (Nyaoro 1996, Kironchi 1998, Mnene 2004). In most areas of pastoral and agropastoral eastern Africa, the coefficient of variation of annual rainfall exceeds 30%. This makes the dynamics of these areas to be predominantly climate-driven and thus non-equilibrium (Ellis *et al.* 1993). This necessitates use of variable stocking rates during the grazing cycle. Therefore, stocking levels have to be adjusted downwards as the dry period sets in and forage availability declines through continuous monitoring.

To enhance favourable water balance in the grazed environment in the study area, surface cover, organic carbon and aggregate stability were the most critical factors. Surface cover and organic carbon are amenable to management. Organic carbon can be enhanced through the application of mulch and manure, while appropriate percent cover can be achieved by observing correct levels of utilization. As pointed out by Liniger and Thomas (1998), surface cover is important in determining the movement of water in a system. Lack of it precipitates high runoffs and sediment loss from grazing land (Thomas *et al* 1981, Kironchi 1998), and leads to rapid degradation of these lands.

The small farm sizes in the study area will continue to pose a management challenge as human population pressure increases. This will particularly affect livestock production that requires large tracts of land in these arid and semiarid environments. Furthermore, individualization of land with exclusive rights of use will continue to threaten access to key grazing resources for those most deserving. Secondary land rights will most likely continue to play a critical role in accessing these resources in the foreseeable future. These rights are particularly suitable as they are flexible and stem from the needs of a particular farming system (Delville *et al*. 2001). Also, secondary rights are important in allocating production factors in the changing circumstances of production systems and in assisting producers to continue producing when their lands are not in production. Secondary land rights embody mobility, a key resource exploitation strategy for tracking grazing resources scattered between cropland and falling under different ownership. Therefore, these rights need to be secured and enforced in all natural resource management institutions.

6.2. CONCLUSIONS

From the results of the current study, the following conclusions can be made:

- Areas of concentrated drainage and sandy-clay plains are key production sites in the production system, absorbing the greatest grazing load during the dry season and wet season, respectively.

- Diet diversities were significantly influenced by animal species and season. Periods of resource scarcity were times of increasing evenness of diversity index, probably brought about by an even use of available forage.
- Goats and cattle exhibited the lowest diet similarity than either sheep and cattle or goats and sheep. Sheep and cattle, and sheep and goats are likely competitive feeders during periods of resource scarcity.
- Animals' energy extraction and consumption is enhanced during the wet season when forages are of higher digestibility than in the dry season when feed digestibility is lower.
- Herded animals generally achieved higher energy intake across the grazing cycle than animals kept under a ranch model. Herding by experienced herdsmen tended to expose animals to microsites of high productivity and dietary quality, thus allowing the animals to achieve higher energy and nutrient intake.
- Animals were in a negative energy balance only in the second late dry season. During this period, more cattle, sheep and goats in the ranch lost weight and were in a negative energy balance than in the agropastoral herds. Therefore, goats maintained a superior position and were relatively hardier than sheep and cattle. This suggests that smallstock, and in particular goats, are more suitable to the area. This is more evident given the higher kidding and lambing percentages realized.
- *Enteropogon macrostachyus* was the single largest primary energy pathway and accounted for over 30% of the total energy intake of cattle. The other important grass resources were *Panicum maximum* (9.9%) followed by *Eragrostis superba* (7.3%). *Combretum exalatum* and *Duosperma kilimandscharica* were the primary energy pathways that accounted for over 10% of total energy intake of goats, with seasonal peaks of 18.5 and 17.2%, respectively. Sheep were largely mixed feeders, but *Enteropogon macrostachyus* (16.6%) and *Blepharis integrifolia* (10.3%) were the primary energy pathways.
- In the studied system, during the growing period, energy intake by cattle is optimized at 420 to 480 gm^{-2} of sward biomass, within a range of grass organic matter digestibility percentage of 55.5 to 64.3.

- Infiltration capacity for the perennial grasses increased with increasing stubble height before levelling off towards the highest stubble height. A 50% removal of current growth is the upper limit above which runoffs and sediment loss from the grass stands increase rapidly. *Panicum maximum* and *Enteropogon macrostachyus* are the most suitable perennial grasses with favourable soil physical properties and infiltration capacity in the area. Aggregate stability, organic carbon and ground plant cover percentage are the most important and significant attributes influencing infiltration capacity.
- Using a growth-consumption rate model, a stocking rate of 7 $TLUha^{-1}$ appears to be the upper limit in this agropastoral system, above which the system's stability is likely to be destabilized during the growing period. To operate above the critical limits, where consumption exceeds production, without affecting system stability will require management strategies that take-off the grazing load till pasture production exceeds consumption.
- A majority of the households use secondary land rights to secure pasture for their animals, in particular short term loans and exchange of bulls for ploughing. These secondary rights give flexibility in dealing with pasture shortages during critical periods. Use of secondary land rights is positively and significantly affected by increasing tropical livestock units per adult equivalent, smallstock to cow ratio and small farm size per adult equivalent. The amount of crop residue available and increasing grazing area per adult equivalent exert a negative effect.

6.3. RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Habitat utilization patterns, critical primary energy pathways, animal seasonal diet diversity, trophic interaction patterns, hydrologic responses of some of the important perennial grasses, and use of secondary land rights to access critical grazing resources were some of the important issues addressed in this study. They are central to sustainable grazing management and livestock production in this semiarid environment. The main recommendations are as follows:

- Plant species diversity in space and time offers a set of primary energy pathways that enhance livestock production in this variable environment. In this respect, any human activities that negatively affect diversity in grazing resources will undermine sustainable livestock production, and thus there is need to control the level of such activities.

- Spatial and temporal variation in forage quality and abundance across the landscape would necessitate livestock to be moved continuously to track this variation as a means of maximizing energy extraction and intake. This will require flexible grazing resource utilization strategies that embody mobility. In this respect, secondary land rights that facilitate mobility and access to grazing resources should be enhanced and entrenched in the production system.
- In light of diminishing farm sizes in the production system, the critical grazing plant resources will require to be improved to produce prolific and high nutritive varieties.
- Grazing management strategies that enhance minimal grazing damage to the environment and complement feeding trophic interactions should be instituted in the production system. This could partly include applying variable stocking rates to match available forage over time, maintaining a removal level of current growth not exceeding 50%, and keeping complementary livestock species, in this case goats and cattle.

Further research in the production system should focus on detailed modelling at small spatial scales to predict energy utilization thresholds and map out energy extraction patterns at patch level to stabilize energy intake over time and minimize risks of resource degradation. This will also require greater understanding of plant attributes that affect energy extraction at patch level.

6.4. LIMITATIONS OF THE STUDY

The following are some of the limitations of the study:

- The study did not address energy extraction and use at household level
- The growth-consumption rate model tested applies only to grazing but not browsing animals
- The results of the study may not apply under very extreme climatic conditions

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ANNEX 1

Questionnaire on grazing land tenure and livelihood strategies

Household population/characteristics of household head

1 Name of household head---

2 Population size per household--

3 a) Is there change in household population size due to migration? Yes/No

b) Which of the following as mainly determined changes in your household population size.

i) Immigration ii) Out migration iii) Seasonal migration.

c) List and rank in importance the main reasons for migrating

i) ii) iii) iv)

v)

4 a) Is the household male or female headed

b) Does the household head have formal education? Yes/No

c) If Yes to b above, at what level? i) Primary ii) Secondary iii) Post-secondary

Land Tenure and Land Use

5 State the approximate land size per household--

6 What is the tenure status of the land?

a) Freehold

b) Tenancy

c) Communally controlled with

i) Permanent individual use right

ii) Temporarily individual use right

iii) Communally controlled and operated

d) State owned and

i) Under lease

ii) Operated by the state

e) Irregular use

7 What tenure rules and user rights exists on grazing lands.

i) Permanent and individual use right

ii) Temporarily and individual use right

iii) Permanent and communal use right

iv) Temporarily and communal use right

8 a) Are there seasonal tenure rules and user rights of grazing fields? Yes/No

b) On which grazing fields

i) Dry season fields

ii) Wet season fields

iii) Others, specify --

9 a) Does the household practice secondary rights on grazing land (i.e. renting in or out of grazing land)? Yes/No.

b) From the following arrangements, state the ones used by the household to rent out or in grazing land?

i) Long term loan ii) Short term loan iii) Exchange of land for cultivation

iv) Exchange of labour v) Exchange of bulls to plough

vi) Others, specify--

10 a) Is there grazing by outsiders without rent on grazing land belonging to your household.

b) Indicate when and on which lands (wet or dry season fields)---------------------------

11 Who enforces grazing land tenure rights? i) Village elders, ii) Chiefs, iii) District tribunals, iv) Law courts

12 a) Are there fines or compensation in case of violation of tenure rights on grazing land?

b) How is the level of compensation determined? --

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13 What is your view on the authority of traditional institutions (village elders) to settle land tenure issues? --

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14 What are the main causes of change in grazing land tenure?

i) ii) iii) iv)

15 What are the principal uses of the land; list and indicate acreage per land use.

i)

ii)

iii)

16 What livestock are kept? Indicate the herd sizes per household

i) ii) iii)

17 Who makes decisions on the herds? --

18 Briefly comment on seasonal herd mobility patterns and grazing management --------

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19 How far are the animals trekked in search of pastures and water (Km)? ---------------

20 Does mobility intensify as the dry season progress? Yes/No

21 a) What are the main constraints to livestock mobility

i) ii) iii) iv)

b) In your view how can these constraints be addressed?------------------------------------

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22 a) Do you use crop residues in livestock feeding? Yes/No

b) What proportion is used in feeding livestock? i) 0% ii) 25% iii) 50% iv) 75% v) 100%

c) How much crop residue is produced per acre (indicate in pick-up loads) -------------

23 a) Compared to the past are the grazing lands degraded? Yes/No

b) What are the main causes of grazing land degradation in your area?

i) ii) iii) (iv)

c) What practices are used to improve the grazing areas. i) Burning

ii) Reseeding

iv). Water spreading iv) Resting areas from continuous use

v) Use of manuals/fertilizers

vi) Others, specify --

d) How do you rate the future of the livestock enterprise in this farming system? i) Bad, ii) Fair iii) Good iv) Very good

Livelihood strategies

24 List the livelihood (survival) strategies used by the household

i) ii) iii) iv)

25 a) Are there livelihood strategies set aside for use during harsh periods like drought?

Yes/No

b) Which ones i) ii) iii)

iv)

26 When do your household invest in livelihood assets? --

27 How do you invest i) Buy more livestock ii) Buy more land for growing crops

iii) Buy more land for keeping livestock iv) Start micro-business v) Bank savings

28 Which livelihood strategies are key to survival of your household. Rank them in order of importance. i) ii) iii)

iv) v)